
Final Report

Puget Sound Physical Oceanography

November 2002

Brightwater Treatment System

**Puget Sound Physical Oceanography Related to the
Triple Junction Region
Brightwater Marine Outfall**

November 2002

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EXECUTIVE SUMMARY

As part of the Regional Wastewater Services Plan, King County plans to construct a new regional wastewater treatment facility in north King County or south Snohomish County by 2010. The treatment plant will have an outfall in the northern part of Puget Sound between Richmond Beach and Edmonds. Currents will dilute and distribute the discharged effluent within and out of this part of the Sound. Therefore, it is important to understand the flow of water in this area. Due to the lack of previous studies and information, King County embarked on several studies. This report describes the results of the studies conducted by King County on the water circulation patterns in the area where Admiralty Inlet and Possession Sound join the Main Basin at the southern end of Whidbey Island, a region called the Triple Junction.

Puget Sound is a deep, glacially carved fjord that connects to the Strait of Juan de Fuca through Admiralty Inlet and Deception Pass. The Strait of Juan de Fuca opens into the North Pacific Ocean between Washington State and Vancouver Island. Within the Sound, shallower sills (underwater shallow bars) separate a series of deeper basins. Proposed outfall locations, between Richmond Beach and Edmonds, are located in the northern portion of the Main Basin.

The study of the Triple Junction took place during July 2000 through January 2002. Observations included current meters, drift cards (floating post-card-sized drifters), drogues (underwater sails), and dye (used as a water flow tracer). As part of King County's study:

- Nine current meters moorings were placed at 56 locations,
- 6100 drift cards were released at 18 locations,
- 106 drogues were deployed at 13 locations,
- Five dye studies were conducted.

In general, circulation in the Triple Junction is very complex, influenced by diurnal (twice-daily) tidal cycles, saltwater inflow from the Strait of Jan de Fuca, freshwater inflow from rivers and streams, and wind.

The tide flows in and out of the Sound twice a day. Each tidal cycle is comprised of an incoming (flood) tide and an outgoing (ebb) tide that are separated by the slack tide, the time between tides when water movement slows to weak and variable and begins to reverse direction.

The complex and irregular shape of the seafloor in this region creates significant variations in tidal currents. Above Whidbey Shoal, located at the southerly tip of Whidbey Island, flood currents generally flow into Puget Sound from Admiralty Inlet and diverge along the eastern shoreline offshore of Browns Bay. North of this divergence, flow is into Possession Sound, and south, into the Main Basin. Ebb currents act similarly in reverse direction. At depths below about 30 meters, flood and ebb currents flow around Whidbey Shoal, and the location of their divergence or convergence is further south, offshore of Edmonds.

Within the Triple Junction, a stronger flood current flows along the western shore between Kingston and Point-No-Point, and stronger ebb currents occur between Richmond Beach and Edmonds. These flows appear to create a counterclockwise rotation in this part of the Main Basin, a result of the irregular shape of the Triple Junction region.

Averaging the flood and ebb currents over a longer period, usually one month, provides a mean current that can be useful in understanding the overall circulation of Puget Sound. Generally, Puget Sound has a mean circulation similar to many estuaries. Saltwater from the Pacific Ocean enters Puget Sound at depth through Admiralty Inlet and then flows southward along the Main Basin and northward through Possession Sound into Whidbey Basin. This basic circulation, or estuarine flow, is created by freshwater flowing into saltwater. The Skagit, Snohomish, and Stillaguamish rivers all empty into the Whidbey Basin area and cause a strong surface outflow from Whidbey Basin. Smaller rivers enter the Sound in the southern portion, resulting in a less intense surface outflow.

Wind action can greatly influence the currents in the Triple Junction area. A wind blowing from the north typically increases the surface water flowing southward out of Possession Sound and hinders water flowing northward from the Main Basin. The opposite holds true, with a southerly wind aiding waters flowing from the Main Basin and hindering water flowing south from Possession Sound. Winds also have pronounced effects on deeper currents. Winds blowing in the direction of the surface current increase both the surface current and flow in the opposite direction at about 100 meters. Winds opposite to the surface flow slow both the surface current and the compensating deep flow.

Drift card studies showed that surface currents primarily exit Puget Sound into Admiralty Inlet and beyond. However, during some flooding tides around Edwards Point, surface water moves towards the shoreline. Then during some ebbing currents, drift cards indicated that water moves onshore between Meadow Point and Boeing Creek. Another finding of the drift card study was a large accumulation of cards in the vicinity of Point Jefferson.

Drogues, or underwater sails equipped with global positioning tracking systems, were used to measure circulation patterns within the Triple Junction. Numerous drogue releases were conducted and drogues were scattered throughout the Triple Junction area. The tracks they made were a complex blend of all factors influencing them, flow, current, tides and wind.

Five separate dye studies were conducted at three depths to examine the near-shore water dynamics. The results showed rapid dilution and dispersal of dye from all release sites.

Prior to this study, relatively little historical data existed for the Triple Junction region. The studies that were undertaken here have added a wealth of knowledge about the tidal and current processes in the area.

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Abbreviations

Argos	Service Argos, Inc., a global geo-positioning services company
ADCP	Acoustic Doppler Current Profiler
cm/s	centimeters per second
°C	temperature in degrees Centigrade
CD	compact disk
CTD	Conductivity-Temperature-Depth sensors
DEQ	Detailed Environmental Question
EH	Evans-Hamilton, Inc.
ft	feet
ft ³ /s	cubic feet/second
gal	gallon
GMT	Greenwich Mean Time
GPS	Global Positioning System
gph	gallons per hour
g/s	grams per second
HDPE	High Density Polyethylene
hr	hour
KCEL	King County Environmental Laboratory
kg	kilograms
kHz	kiloHertz
kn	knots
L	Liter
lb	pound
LIMS	Laboratory Information Management System
m	meters
mi	miles
m/s	meters/second
m ³ /s	meters cubed/second
MDL	Method Detection Limit
mg/l	milligrams per liter
mgd	million gallons per day
MLLW	Mean Lower Low Water tide level
°N	degrees North latitude
NOAA	National Oceanic and Atmospheric Administration
NTU	Nephelometer Turbidity Units

ppb	parts per billion
ppt	parts per thousand
PRISM	Puget Sound Regional Synthesis Model
psu	practical salinity units (approximately ppt)

RDL	Reporting Detection Limit
R/V	Research Vessel
s	seconds
S4	InterOcean electromagnetic current meter
Time	Pacific Standard Time used throughout
µg/l	micrograms per liter
UW	University of Washington
USGS	U.S. Geological Survey
°W	degrees West longitude
WDOE	Washington State Department of Ecology
WT	part of Rhodamine brand name

1.0 INTRODUCTION

As part of its Regional Wastewater Services Plan, King County plans to construct a new regional wastewater treatment system, the Brightwater Project, in north King County or south Snohomish County by 2010. The wastewater treatment plant will have an outfall in the northern part of Puget Sound between the cities of Shoreline and Edmonds. This region is where Possession Sound joins the Main Basin and Admiralty Inlet, and it is called the Triple Junction. Currents will affect the fate of the discharge from this outfall, but only a few historic current observations were available in this complex region. Thus, the prior understanding of the oceanography of the Triple Junction was insufficient to aid in the site evaluation for King County's proposed wastewater outfall, and a new observational study was carried out during July 2000 through January 2002.

The new observations of the oceanography in the Triple Junction were made using several techniques. Current meters were moored to the sea floor to measure currents at fixed locations. Aanderaa and S4 meters measured currents at specified depths along mooring lines. Acoustic Doppler Current Profilers (ADCPs) measured currents throughout the water column by transmitting acoustic pulses from instruments sitting on the sea floor. Because of the lateral complexity of the Triple Junction, current meter moorings for this study primarily were deployed across channel. Drifters were deployed in the water at a variety of depths and moved with the currents. Drift cards floated on the sea surface. Drogues had underwater sails that extended over various 10-m vertical intervals (except 3-m intervals when deployed at the sea surface). Dye was injected at specific depths and was dispersed by the currents.

This report describes water circulation and mixing in the Triple Junction using the new observations synthesized with prior understanding of the region. Prior reports for King County reviewed historic observations (Ebbesmeyer and Cannon, 2001), and provided an interim description of the new observations through June 2001 (Ebbesmeyer et al., 2001).

1.1 Description of Puget Sound

Puget Sound is a glacially carved estuary with a large tidal range of approximately 4 m at Seattle (Figure 1). It connects to the Strait of Juan de Fuca and the Pacific Ocean primarily through Admiralty Inlet and secondarily through Deception Pass. Its long, deep channels interconnect across shallower sills. Sub-regions of Puget Sound include the Admiralty Inlet entrance channel containing two relatively shallow sills, the 200-m deep Main Basin extending from the south end of Admiralty Inlet to Tacoma, and a Southern Basin south of Tacoma and The Narrows sill. There are two major side channels. Hood Canal connects to middle Admiralty Inlet and has a sill at its mouth. Whidbey Basin connects through Possession Sound at the junction of the Main Basin and Admiralty Inlet without a sill. This three-way connection is called the Triple Junction. Although it mostly is deep water (150-200 m), there is an extensive shoal protruding south from Whidbey Island, and a similar shoal extends southeast from Point Jefferson in the Main Basin (Figures 1, 2). Oceanography reviews of Puget Sound include Cannon (1983), Ebbesmeyer et al. (1984), Bretschneider et al. (1985), Ebbesmeyer et al. (1988), Cannon et al. (1990), Lavelle et al. (1991), Thomson (1994), Matsuura and Cannon (1997), and most recently with respect to

the Triple Junction, Ebbesmeyer and Cannon (2001). Numerous references to earlier oceanographic work are in Ebbesmeyer and Cannon (2001).

1.2 Previous Oceanographic Studies

Previous oceanographic studies showed that the important flow characteristics include tidal and wind forcing, the estuarine circulation, and, to a lesser degree, variations in the coastal Pacific Ocean at the entrance to the Strait of Juan de Fuca. Most previous studies focused on along-channel effects. The few cross channel studies showed major flow variations that affect how waters mix within the Main Basin. Few studies have been made within the Triple Junction, but they showed unexpected complexity, partly due to the large shoals off Whidbey Island and Point Jefferson and partly due to the confluence of the three major branches. Also, there have been few studies at triple junctions in other estuaries to help guide the design and analysis of new observations. Tidal currents are not always 180° out of phase, and the mean currents are often not aligned with either the ebb or flood current.

1.3 Currents

The flow in Puget Sound is dominated by tidal currents, but superimposed on that is a time-varying estuarine circulation caused by the surface outflow of fresh water from river runoff and deep inflow of salt water from the ocean. Amplitudes of the tidal currents in the Main Basin are about 50 cm/s, about half as large as those in Admiralty Inlet and twice as large as those in most of Whidbey Basin (Lavelle et al., 1988; Mofjeld and Larsen, 1984). The estuarine circulation is important in transporting water masses and is typically up to about 10 cm/s, but it can be larger during storms and during bottom-water intrusions from Admiralty Inlet (Cannon et al., 1984).

The estuarine component of the flow, forced by dense water from the Pacific Ocean and by local runoff from rainfall and snow melt, generally is a net landward flow of salty water at depth and a net seaward flow of fresher water near the surface. Deep, dense water from the Strait of Juan de Fuca enters Puget Sound through Admiralty Inlet, and part flows south in the Main Basin and part flows north up Whidbey Basin. The largest single source of fresh water in Puget Sound is the Skagit River that flows into the northern end of Whidbey Basin. However, estimates of the fraction of the Skagit River discharge that flows out Deception Pass (21%, 34%, 60%) and that which flows south into the Main Basin and out Admiralty Inlet vary widely (Barnes and Ebbesmeyer, 1978; Cokelet et al., 1990; Collias et al., 1973). Other rivers, distributed throughout Puget Sound, contribute to the region's complex estuarine circulation. The landward flowing deep water replaces the bottom water of Puget Sound and keeps it from becoming stagnant. The outflowing surface water flushes Puget Sound, and it equals the sum of the landward inflow plus the river inflow. The amount of water in each layer depends on the degree of mixing caused by tidal and wind forcing. Vertical mixing over Admiralty Inlet sill plays a major role in this process.

The estuarine circulation in Puget Sound (after the tides have been averaged out) based on compiled results from prior studies is shown schematically in plan view in Figure 1 (from Ebbesmeyer and Cannon, 2001), and it is the working hypothesis used in planning the studies described in this report. The major flow patterns consist of two-layered flow in the three branches joining at the Triple Junction. In addition, the mean outflowing surface current starts from Colvos Passage and flows from side to side in the Main Basin in

response to major topographic features. Higher speeds favor the east side near Alki Point and Point Wells, and favor the west side near Point Monroe and the entrance to Admiralty Inlet. This pattern can result in eddies behind major points with reversed flow nearshore. An example is off Meadow Point north of West Point (Matsuura and Cannon, 1997; Ebbesmeyer et al., 1977).

Figure 1 also shows deep water flowing from the Strait of Juan de Fuca into Puget Sound beneath the upper, outflowing layer. These flows generally are slower than the currents near the sea surface. Deep water travels faster through the Main Basin than through Whidbey Basin because of vigorous upwelling at The Narrows. As the deep inflowing water diverges at the southern end of Admiralty Inlet, the flow component into Whidbey Basin slows compared to the southward flow in the Main Basin.

The schematic mean flow in Figure 1 may be described in more detail as follows: A) northward flow top-to-bottom in Colvos Passage; B) southward flow top-to-bottom in East Passage; C) diverging outflow from Colvos Passage; D) Colvos Passage outflow continues northward with the core concentrated toward Bainbridge Island; E) Point Jefferson Shoal deflects the core eastward toward (E) where most of the flow continues northward past Point Wells and some diverges southward; F) upper-layer outflow turns from Point Wells toward Admiralty Inlet and merges with outflow from Possession Sound; G) surface outflow from Admiralty Inlet to the Strait of Juan de Fuca; H) southward surface outflow in Saratoga Passage; I) divergence of the Skagit River's north and south forks; J) outflow from Deception Pass; K) bottom inflow to Saratoga Passage; L) bottom inflow from Admiralty Inlet diverges with some flowing southward in the Main Basin and some flowing northward into Possession Sound; and M) inflow continues southward in the Main Basin.

2.0 METHODS

This section describes the instrumentation used during the study from July 2000 through January 2002. Current meters were moored at fixed locations, and drogues, dye and drift cards were released to float with the currents. There were current meter moorings at 56 locations, 6,100 drift cards released at 18 locations, 103 drogue deployments, and 5 dye tracer studies. The techniques used with each of these measurements are described in the following sections.

2.1 Current Meters

Three types of current meters were used: Aanderaa RCM4s, InterOcean S4s, and Acoustic Doppler Current Profilers (ADCPs). Aanderaa meters mechanically measure currents with a rotor and vane at fixed depths along a mooring line that is anchored to the sea floor. The Aanderaas record on magnetic tape and were loaned to King County for the project. S4s measure currents at fixed points on moorings like the Aanderaas, except that they have no moving parts and sense current speed and direction by water deforming the S4's magnetic field. ADCPs measure currents through the water column using acoustic pulses transmitted from the instrument on the sea floor. They rely on acoustic echoes of pulses from particles suspended in seawater. Water velocities are computed within the ADCP by estimating the differential current speed of the particles between outgoing pulses and returning echoes (Doppler shift). Currents then were subsampled at 10- or 20-m depth intervals, depending on whether the ADCP was for shallow water (300 kHz; two instruments) or deep water (75 and 150 kHz; two each). Additional ADCPs (1500 kHz) were deployed near shore during deployments 5 and 6 and during dye study 3.

Current meters were deployed for eight intervals lasting one to three months from July 2000 through January 2002. Tables 1 and 2 summarize the deployments, and Figure 2 shows the locations. Exact locations are given in Appendix A. Each ADCP location was designated by a site number. However, all current meters deployed at the same time were also designated both by a deployment number and by a color. For clarity in this report, deployment numbers primarily have been used. After the moorings were initially deployed, subsequent trips recovered the instruments, retrieved the data in the field, and then inspected, refurbished and re-deployed the ADCPs at new locations. Instrument settings are in Appendix B, and detailed deployment statistics are included in Volume 2, Appendix CD-A.

Yearlong moorings were maintained in: (1) Admiralty Inlet to measure deep water inflow using two near-bottom Aanderaa current meters, (2) Possession Sound using two to three Aanderaa meters in the water column with an occasional S4 meter approximately 2 m below the sea surface, and (3) the Main Basin with six Aanderaa meters and an occasional S4 meter. Table 2 summarizes the mean depths of the instruments derived from the Aanderaa pressure measurements. Sample diagrams of the mooring configurations are included in Appendix C. These moorings were serviced at the same time as the ADCPs.

The data return was approximately 98% for the ADCPs and 87% for the Aanderaas and S4 data. ADCPs cannot measure currents in extremely clear water or within about 10 to 20 m of the sea surface and sea floor. Significant data losses included: the upper 20-m bins from

the 150-KHz ADCPs due to signal dropouts (moorings 3, 4, 7, 10, 13, 16); and the upper 40 m of Mooring 43 due to deployment on a steep bottom. Three fixed-point current meters were lost, including an S4 in Possession Sound due to collision with a barge, and two Aanderaas in Admiralty Inlet, presumed due to cable corrosion. Details of the data processing technique are in Appendix D, and the current meter data files are in Volume 2, Appendix CD-B.

Descriptions of the 8 current-meter deployments follow (see Figure 2):

Deployment 1 (Edwards Point Transect) extended across the southern portion of the Triple Junction. Mooring 1 was near the western shore off Apple Cove Point, and Mooring 5 north of Edwards Point. Mooring 6 was near the Main Basin yearlong mooring to intercompare Aanderaa and ADCP current measurements (Section 3.1).

Deployment 2 (Edmonds Transect) extended across the middle part of the Triple Junction. Mooring 7 was on the west, Mooring 9 on the southern end of Whidbey Shoal, and Mooring 12 on the east near Edmonds. Moorings 7 and 8 were in the channel south of Admiralty Inlet and west of Whidbey Shoal, Mooring 9 on Whidbey Shoal, and moorings 10, 11 and 12 in the channel east of the Shoal leading into Possession Sound.

Deployment 3 (Possession Sound and Browns Bay Transects) was along two sections. The northern transect was across the entrance to Possession Sound at the location of the yearlong mooring. Mooring 13 was on the west and Mooring 14 on the east, with the Aanderaa reference mooring between the two ADCPs. The southern transect extended from Whidbey Shoal on the west (Mooring 15) to Browns Bay on the east (Mooring 18).

Deployment 4 (Point Wells Transect) extended from Point Wells to Apple Cove Point. Mooring 19 was closest to the Kitsap Peninsula on the west, and Mooring 24 closest to Point Wells on the east. The Aanderaa reference mooring was between moorings 20 and 21.

Deployment 5 (Admiralty Inlet Transect) extended across the entrance to Admiralty Inlet and onto Whidbey Shoal. This deployment also included deeper moorings (Moorings 35 and 36) at the base of Whidbey Shoal.

Deployment 6 (Point Jefferson Transect) extended across the Main Basin from Point Jefferson (Mooring 39) to Carkeek Park (Mooring 43). In addition, a repeat transect across the entrance to Possession Sound went from Mooring 37 on the west to Mooring 38 on the east, with the Aanderaa reference mooring in the middle.

Deployment 7 (Eastern Shore Transect) extended north-south along the Main Basin from Browns Bay to Carkeek Park (Moorings 46-49). In addition, two moorings (44, 45) were deployed to examine currents along the southern side of Whidbey Shoal.

Deployment 8 (Edwards Point Cluster) was an array with an Aanderaa mooring (50) near mid-channel and three ADCP moorings (51, 52, 53) in a triangle closer to Edwards Point.

Table 1.
Current Meter Deployment Summary.¹

Deployment # (location)	Current meter sites	Beginning date	End date	Comments
ADCP moorings				
1 (Edwards Point)	1-6	July 12-13, 2000	August 21-23, 2000	Moorings 1-5, Edwards Point section; Mooring 6, ADCP/Aanderaa comparison
2 (Edmonds)	7-12	August 23-24, 2000	October 30, 2000	Triple Junction section across Whidbey Shoal
3 (Possession Sound and Browns Bay)	13-18	November 2-3, 2000	January 22-23, 2001	Two parallel sections
4 (Point Wells)	19-24	January 25-26, 2001	March 19, 2001	Main Basin Aanderaa mooring
Dye studies	25-28	March 12, 2001	March 21, 2001	Dye studies
5 (Admiralty Inlet)	29-36	March 21-23, 2001	May 14, 2001	Admiralty Inlet and Whidbey Shoal
6 (Point Jefferson)	37-43	May 16-17, 2001	June 19-20, 2001	Southernmost section
7 (Eastern Shore)	44-49	June 21, 2001	July 25, 2001	North-south section to connect the east-west sections
8 (Edwards Point Cluster)	50-53	November 29, 2001	January 8, 2002	ADCP and Aanderaa meters
Aanderaa moorings				
1-7	Possession Sound	July 13, 2000	July 25, 2001	Deployment 5, S4 lost
1-7	Admiralty Inlet	July 12, 2000	July 25, 2001	Deployment 2, mooring lost
1-7	Main Basin	July 13, 2000	July 25, 2001	Deployment 3, 87 m flooded Deployment 5, 177 m failed
8 (Edwards Point)	Mooring 50	November 29, 2001	January 8, 2002	Part of ADCP cluster

¹ See Figure 2 or Appendix A for locations

Table 2.
Mean Depths for Aanderaa and S4 Current Meters.

Mooring Site	Mean depth (m) ¹
Admiralty Inlet	116, 122
Main Basin	2, 24, 57, 87, 112, 147, 177
Possession Sound	2, 24, 114, 211
Edwards Point	22, 62, 100, 141, 166

¹ Depths were computed from pressure records S4 was at 2 m; other depths are Aanderaas

2.2 Drift Cards

Drift cards offer one of the few practical alternatives to document the currents near the sea surface. They reflect advection and dispersion and have proven over the years to be an effective tool for the determination of near-surface flow.

The drift cards were made from thin pieces of plywood measuring approximately 3x5 inches and coated with orange, non-toxic paint to render them environmentally benign and readily visible en route for beachcombers. Each card was printed with instructions of how to report finding a card, contact street and e-mail addresses, a 800-telephone number, and a serial number to indicate release date and location.

The release sites were determined in the field using the Global Positioning System (GPS). Each deployment released fifty cards per site at sites 1-8 (Deployments 1-9) or sites 9-18 (Deployments 10-14) within a two hour window. Deployments 1 through 9 occurred between August 2000 and August 2001 under various combinations of wind and tide conditions, including 5 ebb tides, 4 flood tides, 6 weak and variable conditions, 2 strong south winds, and a strong north wind (Table 3). Deployments 10 through 14 occurred during November and December 2001, during weak and variable winds.

Drift cards were released on two horizontal scales: Deployments 1 through 9 covered the area between Carkeek Park and Possession Sound, while deployments 10 through 14 were clustered over a smaller area off Edwards Point.

Deployments 1 through 9 used eight drift card release sites located along four transects in the study area (Figure 3): sites 1 and 2 to determine surface current dispersal in the entrance to Possession Sound; sites 3 and 4 off Browns Bay to determine dispersal in the northern part of the Triple Junction; sites 5 and 6 off Point Wells to determine dispersal at the southern part of the Triple Junction; and sites 7 and 8 off Piper's Creek to determine effects of outflowing surface currents in the Main Basin. Inshore sites 2, 4, 6 and 8 were located above the 70-m depth contour, and offshore sites 1, 3, 5 and 7 were positioned approximately 1 mi farther offshore from the respective inshore sites.

Deployments 10 through 14 provided more detailed information on the surface currents in the vicinity of Edwards Point. Ten release sites were oriented along general offshore axes as follows: sites 9 through 11 to the north of Edwards Point; sites 12 through 14 directly off Edwards Point; and sites 15 through 18 off Point Wells. To provide continuity with the Phase 2 releases, Site 16 duplicated the position of Site 5.

To quantify the drift card recoveries, the shoreline of Puget Sound and the Strait of Juan de Fuca were segmented into half-mile intervals. The information provided by the finder was used to assign each drift card to a specific shoreline interval. A daily tabulation of drift card recoveries is included in Appendix E.

Table 3.
Drift Card Deployment Summary

Drift Card Deployment	Date	Release Sites	Number Deployed per site	Total Number Deployed	Deployment Tidal Phase	Conditions Wind
1	Aug 28, 2000	1-8	50	400	Ebb tide	Weak and variable
2	Oct 25, 2000	1-8	50	400	Ebb tide	Weak and variable
3	Nov 30, 2000	1-8	50	400	Ebb tide	Strong south wind (12 kn)
4	Mar14, 2001	1-8	50	400	Flood tide	Weak and variable
5	Apr 12, 2001	1-8	50	400	Ebb tide	Strong south wind (15-20 kn)
6	Apr 20, 2001	1-8	50	400	Flood tide	Strong north wind (15 kn)
7	Jun 7, 2001	1-8	50	400	Ebb tide	Weak and variable
8	Jun 7, 2001	1-8	50	400	Flood tide	Weak and variable
9	Jul 12, 2001	1-8	50	400	Flood tide	Weak and variable
Sub-Total	August 2000 – July 2001	1-8	50	3600	5 Ebbs, 4 Floods	6 Weak and variable 2 Strong south winds 1 Strong north wind
10	Nov 26, 2001	9-18	50	500	Flood	Weak and variable
11	Dec 21, 2001	9-18	50	500	Flood	Weak and variable
12	Dec 22, 2001	9-18	50	500	Flood	Weak and variable
13	Dec 26, 2001	9-18	50	500	Ebb	Weak and variable
14	Dec 27, 2001	9-18	50	500	Ebb	Weak and variable
Sub-Total	November-December 2001	9-18	50	2,500	2 Ebbs, 3 Floods	5 Weak and variable
Total	August 2000 – December 2001	1-18	50	6100	7 Ebbs, 7 Floods	11 Weak and variable 2 Strong south winds 1 Strong north wind

2.3 Drogues

Oceanographic drogues are underwater sails tethered from a surface float. The large underwater sail drifts with the ambient current, allowing the water movement to be traced. In previous studies, drogues were deployed along with dye releases to simulate the dispersion and dilution of effluent from King County's West Point and Renton outfalls (Bendiner, 1976; Ebbesmeyer et al., 1977; URS Engineers et al., 1983).

In this study, 106 drogues were released (Figure 4) and tracked via satellite on 18 occasions for intervals from six hours (a tidal phase) to six days (Table 4). This was the first time drogues have been tracked in Puget Sound for more than a few tidal phases. The subsurface drogues were cylinders, 1 meter in diameter by 10 meters in length, of mesh fabric held open by a number of hoops like an accordion that elongated upon deployment. The drogues were tethered via line to a surface buoy that was connected via stiffened rope to the electronics module. The surface buoy ensured that the Argos/GPS (Global Positioning System) electronics package had a high freeboard and good reception characteristics. The float was tracked via satellite at 30-minute intervals. Trajectory plots

of each deployment are included in Appendix F;. Volume 2 Appendix CD-C contains the data files.

The first three deployments (A, B, C; once over a tidal phase and twice over a day) were utilized to develop confidence and experience in using the drogues over progressively longer durations. The remaining drogue deployments were carried out over three to six days. Trajectories are described in Section 4.2.

Drogue deployments A through K released a drogue at each release location in a relatively synoptic manner, usually within a two hour window. For each dye release, drogues were released near the dye injection site, at periodic intervals throughout the dye release. In conjunction with two University of Washington Oceanography 460 students (Hoglund, 2001; Burcal, 2001) near surface drogues were released in a similar manner to deployments A through K.

2.4 Dye

Five dye tracer studies were conducted (four in 2001; one in 2002) to observe vertical mixing and interaction of offshore waters with nearshore water. The principal objective of these studies was to assess the potential for offshore water at various depths to be transported onshore toward shallow beach areas.

Dye studies were conducted during the weeks of February 5, March 12, May 7, June 5, 2001, and February 4, 2002. The February 2001 and May injection sites were in Browns Bay vicinity, and the March and June injection sites were in the Point Wells vicinity. The fifth dye study was conducted from an injection site in the vicinity of Edwards Point. Detailed descriptions of each experiment are in Appendix G and the associated data files are in Volume 2 Appendix CD-D.

A 500-gph pump was used to circulate ambient water onto a research vessel moored above the injection site, where it was combined with the dye. The dye was injected into the circulating ambient water with a progressive-cavity sample pump set and calibrated at a rate of approximately 3.8 gph for the first four studies, and 7.4 gph for the fifth study. The dye and circulating sea water solution were then discharged at selected depths through a 6 m long vertical diffuser. Hourly CTD casts were obtained from the moored injection station to document the density of the dye solution versus the ambient density at the diffuser depth. Dye discharge was monitored hourly by measuring the amount of dye remaining in the container.

Table 4.
Drogue Release Summary

Release	Date	Number Tracked	Depth (m)	Duration	Deployment Tidal Phase	Wind Conditions¹
A	Aug 3, 2000	6	30-40	6 hours	Ebb	Calm
B	Aug 28-29, 2000	8	1	24 hours	Ebb	North ~5 kn
C	Sep 13-14, 2000	6	20-30	24 hours	Flood	North ~5 kn
D	Oct 25-31, 2000	7	20-30	6 days	Flood	North 1.5d @ 5 kn South 2d @ 10 kn North 2d @ <5 kn
E	Nov 30-Dec 6, 2000	8	20-30; 100-110	6 days	Ebb	South 3d @ 10 kn North 3d @ 10 kn
F	Jan 17-24, 2001	8	50-60; 120-130	6 days	High Slack	Day 3-5 South @ 10-15 kn
G	Apr 25-May 2, 2001	6	50-60; 120-130	6 days	Ebb	Day 1 North @ 5 kn Day 2-6 South @ 10-15 kn Day 4-5 South @ 15-20 kn
H	Jan 8-10, 2002	6	3@50-60; 3@150-160	3 days	High Slack	Day 1 South @ 10 kn Days 2,3 South 5-10 kn
I	Oct 29-Nov 1, 2001	7	70-80	4 days	Flood	Days 1,2 5-10 Days 3,4 South 15 kn
J	Nov 12-17, 2002	7	70-80	5 days	Flood	South 10-20 kn
K	Nov 26-Dec 4, 2001	7	50-60	4 days	Ebb	South 5-30 kn
Dye 1	Feb 5–9, 2001	7	3-13	4+ days	Ebb	Day 2: NW @ 10-15 kn
Dye 2	Mar 12–16, 2001	5	3-13	3 days	Ebb	Day 2: NW @ 10-15 kn
Dye 3	May 7-11, 2001	4	20-30	3 days	Ebb	North 5-10 kn
Dye 4	Jun 5-9, 2001	4	20-30	4 days	Ebb	North 5-10 kn
Dye 5	Feb 4-7, 2002	4	50-60	4 days	Minor flood and ebb cycle	Day 2,3 South 15-20 kn
UW460a	Mar 26-Apr 2, 2001	3	3-13	6 days		Day 1-2 South 10 kn Day 3-6 North 5-10 kn Day 5 10-15 kn
UW460b	Apr 3-5, 2001	3	1	3 days		South 5 kn
Total	18 releases	106 drogues		69 days		

¹ Winds blow from the indicated directions.

Rhodamine WT fluorescent dye was injected at the expected trapping depths of candidate outfall sites selected for the tracer studies. Each dye injection period lasted approximately 12.4 hours, or one semi-diurnal tide period. Dye concentrations were continuously measured at key nearshore monitoring stations during and following the dye injection period. Direct plume measurements from a towed instrument were also obtained in the far field from a boat equipped with a fluorometer.

Shoreline samples were obtained in two ways. Autosamplers were used to collect samples at 30 minute intervals as composites of three samples taken at 10 minute intervals. Samples were collected daily and transported in dark containers to King County's conventional parameter laboratory. At locations impractical to install autosamplers, sample sites were visited by crews in small boats or from land, collecting bottle samples by hand on 1- to 2-hr cycles. Samples were stored in dark containers and transported to the laboratory at regular intervals.

The dye measurements were made with a Turner Designs Model 10-AU set up in the discrete sampling mode. Dye standards from the Rhodamine dye furnished by Keystone Industries were prepared according to standard serial dilution procedures by King County personnel (Turner Designs, 1991). All field samples were calibrated to the dye standards during each study. Background samples were also obtained and measured before each injection period.

3.0 CURRENT METER OBSERVATIONS

This chapter summarizes the currents measured by the ADCP and Aanderaa current meters. These meters typically recorded current speed and direction at hourly intervals at various depths for periods of a month or more. The flow pattern within the Triple Junction Region, as recorded by these meters, is very complex. Section 3.1 discusses the procedures employed to analyze this data and extract overall circulation trends. The tidal flow, the twice daily flood and ebb of water, is characterized in Section 3.2. Removing this tidal flow from the data helps reveal the overall circulation pattern. The overall circulation pattern has variations from day to day and week to week, which is discussed in Section 3.3. Section 3.4 summarizes the mean circulation pattern as observed at east-west cross sections extending across the Triple Junction. Section 3.5 presents a more detailed analysis of the vertical variation of currents with depth. Current observations from drifters are reported in Chapter 4.

For the purposes of illustration, depths of 20, 60, 100, and 140 meters were selected to present the flow on maps. The shallower two levels are above (20 m) and below (60 m) the horizon of Whidbey Shoal (approximately 30 m). The deeper two levels are in mid-depth (100 m), and in the deep water (140 m).

3.1 Analytical Methods

Analysis of the current meter data was carried out with a variety of techniques described in the following sections.

3.1.1 Tidal Currents

The flood and ebb tidal currents were obtained by creating a frequency histogram of the observed current directions. Histograms were created at 20-meter depth intervals for each ADCP meter, and at the depth of each Aanderaa meter. Current directions were separated into 20° increments, and the two preferred directions of flow gave the flood and ebb directions. The average speeds in the two 20° sectors were calculated to represent the general ebb and flood currents and were plotted at the center direction of the sector.

3.1.2 Filtered Currents

Low-pass Filtering

To examine longer-term variability of currents, a 35-hr Lanczos filter was applied to the current meter time series. This filter is optimized to suppress tidal currents while leaving the variability due to winds, intrusions and other low-frequency phenomena, and it has been extensively used by NOAA since the 1970s (Charnell and Krancus, 1976). Specifically, the filter was applied to the north- and east-speed components that were then combined to compute hourly velocity vectors. This filter effectively removes the periodic tidal components, passing only 0.1% of the amplitude at periods of 25 hrs, while 50% is passed at 35 hrs and 99% at 55 hrs. Details of this filter are in Emery and Thomson (1997). The filtered current vectors are representative of the net motion over a tidal cycle. Selected

time series are discussed further in Chapter 5, and the entire low-pass filtered time series are in Volume 2 Appendix CD-E.

Current Modes

To compare current meter measurements from separate deployments, a technique was needed to describe the spatial distribution of flow. Empirical orthogonal function (EOF) analysis has been used to analyze simultaneous observations from individual cross sections (Bretschneider et al., 1985; Matsuura and Cannon, 1997), and similar techniques have been applied to horizontal arrays (Emery and Thomson, 1997). However, this technique was not suitable to this data set as the observations are not simultaneous. Instead, an objective technique was developed to determine the dominant modes of flow, or the distributions of the low-frequency flow patterns that occurred most often.

Current modes refer to the most frequent, or prevalent, current directions. For the original hourly observations of current speeds, the two predominate directions correspond to the flood and ebb tidal currents. Histograms of the low-pass filtered current record may show several preferred directions. The most frequent direction is labeled mode 1, the next most frequent mode 2, and so on. Up to three modes were identified at each current meter, based on the criterion that a mode had to account for at least 10% of the observations. It is often possible to relate a current mode to a specific forcing mechanism, such as winds or bottom-water intrusions.

To determine the current modes, histograms of frequency of flow directions were calculated from the low-frequency (Lanczos-filtered) data. The histograms were plotted in 20° direction increments and at 20-m depth intervals for each ADCP and at the depth of each Aanderaa current meter. The frequency of flow is shown as the radius of the shaded sector, and the most frequent flow direction, or mode 1, is the sector with the largest radius. In this study the most frequent sector was used to represent the mode, but the modes may represent clusters of two or more adjacent 20° sectors.

The average current speed for each mode was calculated from the vectors within each 20° sector and was plotted along the center direction of the mode.

To illustrate the process of selecting modes, Figure 5 shows sample histograms and modal currents for two locations. The full histograms for both unfiltered and low-pass filtered currents are compared with the selected directions and speeds of the dominant modes, and with the more commonly calculated mean currents. The first example from Mooring 22 off Point Wells shows ebb and flood currents approximately 180° out-of-phase and filtered currents in one general direction. The ebb current is greater than the flood, and the modal mean current is approximately the same as the mathematical mean. This is a case in mid-channel and is what is commonly expected for flow in an estuary. However, the second example from Mooring 4 off Edwards Point is much different. Ebb and Flood currents are considerably different from 180° out of phase. The low-frequency histogram shows three modes, and mode 3 is in the direction of the mathematical mean current, but about twice the magnitude. Also, the mode 1 current, most frequent, is smaller than the mode 3 current. The causes of the different modes are discussed in Section 3.3.

Maps of low-frequency currents at 20, 60, 100, and 140 m are described in Section 3.3.

3.1.3 Mean Currents

Mean currents were computed over 28-day intervals for each current meter record. This interval contains an integer number of tidal cycles, and many historical data have been averaged over this interval. The number of 28-day intervals per deployment depended on duration of the deployment (Table 5). Deployments 1, 6, 7, and 8 each lasted about a month permitting calculations of 28-day means. Deployments 2, 4 and 5 lasted about two months enabling two 28-day means, and Deployment 3 lasted 80 days, long enough for three 28-day means that did not significantly overlap. Mean currents were computed for 13 28-day intervals during deployments 1-8 in this study.

Each Aanderaa mooring was comprised of several meters that measured currents at discrete depths. The meter depths varied slightly between each deployment, so for each deployment depths were determined from each meter's pressure gauge and then averaged for the entire year (see Table 2). Aanderaa mean currents are plotted on composite current maps within 5 m of the Aanderaa meter.

Cross sections of mean currents are discussed in Section 3.4, and Aanderaa mean current profiles, in Section 3.5. The large number of current modes in the Triple Junction region create some uncertainty in using the more traditional mean currents, and this report shows the low-frequency flow primarily with modal current maps. Composite maps of 28-day mean currents at 20-m intervals for the ADCP data are shown in Appendix H.

3.1.4 Volume Transport

Volume transports were estimated by placing a grid of rectangles over contours of 28-day average current speeds through various sections. Transport within each rectangle was estimated by multiplying the area times the mean current at the center. The transports were then summed separately for the northward and southward flowing layers. Volume transports were calculated for the cross-sections offshore of Edwards Point during Deployment 1 (July - August 2000) and offshore of Point Wells during Deployment 4 (February – March 2001)

Table 5.
Dates for 28-Day Mean Currents

Deployment #: Location 28-day segment code	Start date	End date
D1: Edwards Point Section		
1. D1	July 14, 2000	Aug. 10, 2000
D2: Edmonds Section		
2. D2a	Aug. 24, 2000	Sept. 21, 2000
3. D2b	Oct. 4, 2000	Nov. 1, 2000
D3: Possession Sound Sections		
4. D3a	Nov. 3, 2000	Nov. 30, 2000
5. D3b	Dec. 1, 2000	Dec. 28, 2000
6. D3c	Dec. 27, 2000	Jan. 22, 2001
D4: Point Wells Section		
7. D4a	Jan. 27, 2001	Feb. 23, 2001
8. D4b	Feb. 20, 2001	Mar. 20, 2001
D5: Admiralty Inlet Section		
9. D5a	Mar. 24, 2001	Apr. 20, 2001
10. D5b	Apr. 16, 2001	May 13, 2001
D6: Point Jefferson Section		
11. D6	May 18, 2001	June 14, 2001
D7: Eastern Shore Section		
12. D7	June 21, 2001	July 25, 2001
D8: Edwards Point Cluster		
13. D8	Nov. 30, 2001	Dec. 27, 2001

3.1.5 Winds

A substantial portion of the low-frequency current variability is correlated with the surface winds. Time-series observations of wind speed and direction were obtained from Paine Field airport for comparison with the current meter observations. Paine Field is located in Everett, slightly east of Possession Sound (Figure 2). Spatial variations of wind speed and direction within the Triple Junction region were occasionally obtained from anemometers on the Washington State ferries (<http://www.atmos.washington.edu/maciver/Ferry/Ferryjs/mainframe1.htm>).

A visual inspection of time-series correlation was used to suggest when current observations were influenced by wind effects. This is discussed in Section 3.3.

3.2 Tidal Currents

Tidal currents, representing the twice daily ebb and flood of water, are driven by the gravitational attraction of the sun and moon. In a straight narrow channel, the ebb and flood currents would be 180° out-of-phase. Ebb and flood currents are shown for each current meter at depths of 20, 60, 100, and 140 m in Figures 6 through 9. Off Point Wells, ebb vectors point north and flood vectors south, as expected for a narrow channel. However, in the topographically complex Triple Junction, particularly near Edwards Point, ebb and flood directions exhibit oblique angles.

The influence of the Whidbey Shoal can be seen from a comparison of the tidal currents at the 20-m depth level with the deeper levels. The 20-m depth level is above the average depth of Whidbey Shoal (about 30 m), while the deeper levels lie below it.

Tidal Currents: 20 m

Figure 6 shows that the incoming flood currents over Whidbey Shoal diverge between Edwards Point and Browns Bay. The onshore flood currents and divergence in this region helps explain the large number of drift cards found in this location and the grounding of numerous drogues. The ebb currents show a similar pattern in reverse. In the Main Basin and in the Triple Junction, ebb currents generally exceed flood currents, indicating the mean seaward flow. Flood currents exceed ebbs in Possession Sound, suggesting that the outflowing layer is shallower than 20 m. There also is a slight indication that floods exceed ebbs close to the Kitsap Peninsula.

Non-complementary angles between ebb and flood occur at numerous locations, off Edwards Point, in the divergence-convergence region off Browns Bay, over the Whidbey and Point Jefferson shoals, and on the west side of the Point Wells section. Other studies have found that the presence of a headland can create oblique angles between flood and ebb currents. Depending on the geometry of the location, this effect can produce mean currents that are onshore (Geyer and Signell, 1990) or offshore (MacCready et al., 2001).

Tidal Currents: 60 m

Figure 7 shows that the incoming flood currents are west of Whidbey Shoal and are directed toward Edwards Point. The flood divergence appears to occur a little to the north

of the point, but farther south than at 20 m, although this is difficult to determine with the resolution of the data. Flood currents just off Edwards Point are southward. Ebb currents from Possession Sound and the Main Basin generally convergence on a line toward the southwest end of Whidbey Shoal, about the same location as where the flood currents diverge. Across the Point Wells section, flood currents are greater on the west side and ebbs on the east side. There are fewer occurrences on non-complementary flows, but they occur at several locations off Edwards Point and close to shore at other locations. There also appears to be some up and down canyon flow on the south end of Whidbey Shoal.

Tidal Currents: 100 m

Figure 8 shows that flood currents exceed ebb currents at most locations except along the east side of the Point Wells section. The divergence-convergence is particularly evident on a line between Edwards Point and the southwest end of Whidbey Shoal. Closer to Edwards Point the flow is parallel to shore, southwestward on flood and northeastward on ebb. Drogue trajectories were like those explained at 60 m.

There is a pronounced headland effect off Point Jefferson that results in eastward cross-channel flow. This effect contributes to recirculation within the northern Main Basin and is the southern limit of that effect.

Tidal Currents: 140 m

Figure 9 shows flow patterns similar to those at 100 m. Floods exceed ebbs everywhere, and the divergence-convergence region is clearly off Edwards Point. Non-complementary ebbs and floods occurred at fewer locations than at shallower depths.

3.3 Low-frequency Currents

In Section 3.2, the directions of ebb and flood currents at certain locations were observed not to be 180° out-of-phase, particularly near the boundaries. In these cases, the residual circulation, after the tidal motion was removed, bisected the directions of ebb and flood currents. To better understand the implications of these features, the approach described in Section 3.1 was used to determine dominant modes of flow, that is, the distributions of the low-frequency flow patterns that occurred most often. Histograms of the low-frequency currents, often called current roses, at depths of 20, 60, 100, and 140 meters are given in Appendix I.

The magnitude of the corresponding current modes are shown in Figures 10 through 13. The current modes were determined using the procedure outlined in Section 3.1. Each current mode represents at least 10% of the observations. The moorings with fewer modes had a more uniform current distribution. The low-frequency current mode speeds are of similar magnitude to the 28-day mean currents away from the coastal and submarine boundaries. However, in regions of multiple modes, the traditional mathematical mean currents are less meaningful.

This new way of describing low-frequency modal currents is useful to describe nonsimultaneous observations of flow in a complex region like the Triple Junction. However, this modal analysis can not capture coherence between different locations, because of the non-simultaneity of the observations. For this reason, it was not possible to

rigorously define all the variations because seasonal (temporal) changes can reverse the relative distributions between secondary modal currents.

Low-frequency Currents: 20 m

Figure 10 shows the magnitude of the modal speeds at 20 m. At this depth, mode 1 appears to represent the general estuarine outflow from the Main Basin into both Admiralty Inlet and Possession Sound. The flow over Point Jefferson Shoal has a large eastward component directed toward the eastern shore near Point Wells. From there the flow diverges about mid channel with the western side directed toward Admiralty Inlet, and the eastern side flowing toward Possession Sound after passing Edwards Point. The flow toward Possession Sound converges with the outflow from Possession Sound, and a portion appears to be redirected westward over Whidbey Shoal. This westwardly flow then converges with the flow exiting directly from the Main Basin.

Along the shore north of Edwards Point, the flow is more variable and has some onshore components. The overall pattern appears to flow towards Possession Sound, turning westward and flowing over Whidbey Shoal between Browns Bay and Picnic Point. In Possession Sound the currents are stronger with inflow along the eastern shore and a well-defined outflow along Whidbey Island.

Mode 2 is mostly wind-induced variability that is explained in more detail in Section 5.4. Briefly, southerly winds (blowing to the north) augment outflow in the Main Basin but retard it in Possession Sound, and vice versa for northerly winds (to the south). The Triple Junction is an interaction area between these two effects. In this region, winds from the south augment mode 1, but winds from the north force flow from Edwards Point to shift toward Possession Sound.

Low-frequency Currents: 60 m

Figure 11 shows the flow at 60 m. Mode 1 is outflow from the Main Basin and inflow into Possession Sound. The outflow off Point Wells divergences at mid channel as it did at 20 m. The west-side flow is toward Admiralty Inlet, and the east-side flow is toward Possession Sound. There is a large cross-channel variation at the Admiralty Inlet entrance with outflow on the west and inflow on the east, and this pattern reverses for mode 2. Flow at this level is mostly confined to go around Whidbey Shoal, with the exception of the down-canyon flow on the south side of the shoal. Within the Triple Junction, there appears to be convergent flows from Admiralty Inlet and the Main Basin toward Possession Sound. The discrepancies may be a result of non-synoptic sampling.

Mode 2 is mostly wind induced variations, similar to those at 20 m, but concentrated off Edwards Point.

Low-frequency Currents: 100 m

Figure 12 shows the flow at 100 m. Mode 1 is the general southward estuarine inflow from Admiralty Inlet that extends along the western side of the Triple Junction to the Point Jefferson Shoal. A portion of the flow appears directed toward Edwards Point from the west end of Whidbey Shoal diverging north or south closer to Edwards Point. Northward flowing water off Point Wells extends down to 120 m, and this deep northward flow continues to Edwards Point where it converges with the Admiralty Inlet inflow.

Mode 2 variations are thought to be primarily wind induced, as discussed in Section 5.4. At this depth, the wind effect is to create a compensating flow that is opposite in direction to the near-surface effects. For example, a wind to the north off Point Wells augments surface outflow, but it increases the southward flow on the west side and decreases northward flow on the east side. The region off Edwards Point appears extremely complex. Modes 2 and 3 are complicated, showing either the continuation of the easterly flow from Whidbey Shoal, or north or south flows. The direction of the low-frequency flow at this depth vary due to compensating flows for wind events or bottom water intrusions (see Section 5.5), in addition to the general estuarine flow.

Low-frequency Currents: 140 m

Figure 13 shows the flow at 140 m. Mode 1 appears to represent the general estuarine inflow from Admiralty Inlet into Puget Sound. The inflow is confined west of Whidbey Shoal and then diverges into the Main Basin and Possession Sound. Inflow occurred across the entire Point Wells section and south of Point Jefferson, and its magnitude was greatest on the west side and decreased to the east. This trend also was evident on all the deep mean current maps (Appendix H).

Mode 2 has large variations off Edwards Point that appear to be a major divergence of the main inflow. Depending on the strength of the inflow, the flow near Edwards Point is north or south as noted above with the 140-m histograms.

3.4 Mean Current Cross Sections

This section discusses the overall circulation of the Triple Junction region, as represented by 28-day averages of the observed currents. Calculation of mean current vectors is a common approach to describing an overall circulation pattern, representing the net motion away from the measurement site and averaging out both tidal and low-frequency fluctuations. In many estuaries, the flood and ebb are completely out of phase and the mean current is in the direction of the flood or ebb. When the ebb and flood directions are not exactly 180 degrees out of phase, as in portions of the Triple Junction Region, the mean current will be in a direction between the flood and ebb. Using mean currents to infer where water moves involves the assumption that the currents do not vary in the distance water travels while fluctuating around the measurement location. This is often a reasonable assumption, however some regions of the Triple Junction, particularly near shorelines, exhibit closely-spaced changes in tidal and low-frequency current directions. Nonetheless, the mean currents presented here are believed to be representative of the overall circulation.

Figures 14 through 27 show 28-day mean currents perpendicular to seven vertical sections (Figure 2): Point Jefferson, Point Wells, Edwards Point, Edmonds, Browns Bay, Admiralty Inlet, and Possession Sound. Three additional figures (Figures 28-30) show the cross-channel flow components for two of the sections: Point Wells and Edwards Point. Multiple figures are presented when observational record allowed multiple 28-day averages to be extracted (see Table 5). Note that the speed scales change from section to section, but the color coding has the same sense: red is the fastest outflow; the transition from yellow to green is the depth of no-net-motion, and blue is the fastest inflow. Blank areas near the surface and bottom occur because the ADCPs cannot determine currents in those regions (Section 2.1).

Dates and durations of each deployment was summarized in Table 1, and the individual mooring locations are shown in Figure 2.

Maps of the mean currents are presented in Appendix H.

Point Jefferson Section

Figure 14 shows the currents through the section extending southeast from Point Jefferson to Pipers Creek. Northward outflow generally occurred through the section above 40 m except on the eastward site, near Pipers Creek, where weak currents extended down to approximately 90 m. Maximum outflow exceeded 12 cm/s, and was greater than the maximum inflow of 4 cm/s observed between 100 and 250 m. However, the magnitude of the deep current is understated in this analysis, as the deep flow has a significant component in the direction of the transect (Figures 12-13). Mean currents at depth tend to be southeasterly in direction and exceed 10 cm/s.

Point Wells Section

Mean current cross-sections are shown for the first and second month of the deployment extending westward from Point Wells to the Kitsap Peninsula in Figures 15 and 16, respectively. The depth of no-net-motion, above which flow is northward, shoaled from 120 m off Point Wells to the sea surface off the Kitsap Peninsula. The northward outflowing water had a core of higher velocity, exceeding 14 cm/s, centered at Mooring 21. The deep southward inflow had speeds exceeding 16 cm/s concentrated on the west side. Inflow-outflow magnitudes were greater during the second month of this deployment (February through March).

Figures 28 and 29 show the cross-channel components of the currents on this section for the first and second 28-day periods. Flow west of Mooring 22 had a westerly component, directing northerly flow parallel to the shoreline towards Admiralty Inlet, and southerly flow towards the Pt. Jefferson Shoal. Flow to the east of mooring 22 was primarily north-south, with only a minor (< 1 cm/s) component in the east-west direction.

Edwards Point Section

Figure 17 shows currents through the transect extending from near Edwards Point westward to Apple Cove Point on Kitsap Peninsula. As in the Point Wells section, the level of no-net-motion is at the surface near the Kitsap Peninsula and deepens to the east to 140 m off Edwards Point. There is a core of outflowing water exceeding 12 cm/s centered near Mooring 4 on the east side, and the southward inflow exceeds 8 cm/s and is concentrated on the west side. There is a sharp north-south gradient near Mooring 2 between the core of northward outflowing water and the southward inflowing water.

Figure 30 shows the cross-channel components of the currents on this section. There is a core of westward flow component corresponding to the northward core at Mooring 4. Thus, the major flow in this section is directed toward Admiralty Inlet. The eastward flow components elsewhere are correlated with the southward flow, showing the southeastward direction of the inflow from Admiralty Inlet. The east-west currents in this section are reversed compared to those in the Point Wells section, and are correlated with the north-south flow, while those in the Pt Wells section were relatively uniform over the entire depth.

Edmonds Section

The Edmonds section was located between the Admiralty Inlet and Edwards Point sections, crossing Whidbey Shoal at its southern end at Mooring 9. West of the shoal, the level of no-net-motion reached the surface near the Kitsap Peninsula. Northward flow occurred through most of the section over and east of the Whidbey Shoal. The core of the outflowing water was located near mid-channel with mean currents of about 15 cm/s over the shoal. Southward flow occurred close to the Kitsap Peninsula. Beneath the depth of Whidbey Shoal, southward flow on the west was saltier water from the Strait of Juan de Fuca, and the northeastward flow east was the divergence of part of the saltier inflow water that enters the deep Whidbey Basin.

The southward surface outflow observed in the Main Basin along the Kitsap Peninsula could extend as far north as about midway between Apple Cove Point (Edmonds Section) and Point No Point (Admiralty Inlet Section). This southward surface layer flow is part of a recirculation process within the Main Basin discussed in Sections 4.2 and 6.

Admiralty Inlet Section

Figures 20 and 21 show flow through the section from the Kitsap Peninsula to Whidbey Shoal and then through the north-south section across the shoal to Whidbey Island. Outward flow occurs across the entire section, above 80 m on the western side, above 50 m nearer Whidbey Shoal, and at all depths over the shoal. During the first month (March - April) the core of high northward velocity, exceeding 10 cm/s, occurred at mid channel, and the highest inflow, exceeding 14 cm/s, also occurred at mid channel in the deepest portion of the section. During the second month (April - May) the mean flow is 25-50% weaker than the first month. This reduction in the mean flow is a result of the increased occurrence of mode 2 low-frequency currents (Figures 10-13) during this month.

Overall, these cross-sections show the estuarine flow of Puget Sound. The inflow of water from the Strait of Juan de Fuca is seen below 40-90 meters, with a shallower outflow above and over Whidbey Shoal.

Browns Bay Section

Figures 22 to 24 show contours of along-channel speed for the three 28-day averages of Deployment 3. These sections extend from Browns Bay on the east, then trend northwest to Whidbey Shoal.

Taken together, the three sections show currents are toward the north and south and alternate across the section. The strongest northward currents occur in a core just east of Whidbey Shoal, and near the bottom off Browns Bay. Between the two bands of northward currents, the currents flow southward along the eastern slope of Whidbey Shoal and near the mid-portion of the section.

Possession Sound Section

Figures 25 through 27 show the 28-day mean currents for the three months measurements were made at the Possession Sound section. Three depth layers are evident. The upper layer consists of a southerly flow of fresher water out of Whidbey Basin. Much of this layer is less than 20 meters thick and was not captured by the ADCP current meters. The

largest currents appear to be in the thickest part of the upper layer toward the western shore along Whidbey Island. This outflow appears to go around the end of Whidbey Island and across the shoal, as seen in the shallow outflow in the Admiralty Inlet Cross-Section.

The middle layer flows into Possession Sound in the general depth range from 40 m to approximately 140 m. The largest inflow occurred beneath the largest outflow in the upper layer (western side) reaching speeds of 5 cm/s. The third and deepest layer flows out of Possession Sound at depths greater than approximately 140 m.

3.5 Mean Current Profiles

In order to validate combining the observations made with the two major types of current meters (ADCP and Aanderaa), an intercomparison experiment was conducted during Deployment 1. ADCP Site 6 was located near the long-term Aanderaa mooring (Figure 2; Table 1). Figure 31 shows 28-day mean currents from the Aanderaa current meters and the ADCP, as well as the mode 1 currents. Mean speeds were designated as outflow if the directions had a north component, and inflow if the mean speeds had a south component. This approximation was reasonable because this site lies along a north-south oriented portion of the Main Basin. The mode 1 currents are very similar to the mean currents in this comparison, since only a single mode is evident at this location.

Figures 32 and 33 show mean current profiles at the three Aanderaa current meter reference moorings in the Main Basin, Possession Sound, and Admiralty Inlet for the periods of November – January and January – March, respectively. These periods are presented to illustrate the near-surface currents. A near-surface S4 current meter was on the Possession Sound mooring during Deployment 3 (November – January) and on the Main Basin mooring during Deployment 4 (January – March). These sites were maintained for a year-long period during the first seven ADCP deployments, although the Admiralty Inlet mooring was lost during Deployment 2. Profiles for all Aanderaa deployments are shown in Appendix J. The mathematical mean currents are used here and are the same as those used in the mean current transects in the previous section and in mean current maps in Appendix H.

The current profiles show the vertical variation in velocity, similar to the vertical cross sections presented in Section 3.4 (Figures 14-27). There are significant differences between the profiles in the Main Basin and Possession Sound. The Main Basin is two-layered with zero velocity at about 80 m, and the profiles for the two deployments are basically identical (Figures 32-33). Observations at three depths in 1982 were similar to these profiles (Ebbesmeyer and Cannon, 2001). In contrast, Possession Sound is characteristic of the middle reaches of a fjord. In this case, the sill is far downstream at Admiralty Inlet and the major river input is far upstream beyond Possession Sound (Cannon et al., 1984). The level of no-net-motion is near 20 m for two of the three profiles, and below 20m for the third (Figure 32). The level of no-net-motion is uncertain for the third profile due to the lack of meters between 20 and 110 m. Interpolation from neighboring ADCP meters suggests a depth of 30-40 m (Figure 26). The merging of the two different flow patterns in the Triple Junction is complicated as shown in the maps of low-frequency currents (Figs. 10-13).

Figures 32 and 33 show the two-layered flow at the Aanderaa site in the Main Basin. The fastest outflow and inflow were 10 to 15 cm/s and occurred at the surface and bottom,

respectively. The depth of no-net-motion occurred at 75 to 80 m. During the second 28 days of Deployment 4, there was both stronger surface outflow and bottom inflow. This may be caused partly by stronger bottom-water intrusions.

The Main Basin reference mooring was located about midway between moorings 20 and 21 during Deployment 4 across the Point Wells cross-section (Figures 15-16). The level of no-net-motion varied from 120 m near Point Wells to near the surface between moorings 19 and 20. The 75-m depth of the no-net-motion for the second 28-day interval at this site (Figure 33) is approximately midway between the 100-m level at Mooring 21 and the 50-m level at Mooring 20.

Figure 32 shows a classical fjord circulation in Possession Sound. There is a relatively shallow outflowing layer with the largest speeds near the surface and decreasing inflow with depth. The S4 current meter at 2 m measured surface outflow with speeds exceeding 25 cm/s. Beneath the outflow, there is a much deeper inflowing layer with the largest speeds at mid-depths. This is different from the typical circulation in most shallower estuaries and in the Main Basin that have more nearly equal depth ranges of outflow and inflow.

Vertical profiles of mean currents for ADCP moorings 13 and 14 in Possession Sound for Deployment 3 showed large cross-channel variations (in cross section in Figures 25-27). The near-surface outflow is dominant on the west side and extends down to about 40 m. Outflow at the Aanderaa mooring in mid-channel extended down to about 20 m. Thus, the level of no-net-motion appears to slope upward from west to east, possibly reaching the surface on the east side of Possession Sound. Outflowing freshwater is located within the core of higher velocities closer to Whidbey Island as it leaves Possession Sound. Inflow occurred in a mid-depth layer on the west side extending from about 40 m to 150 m, with maximum speeds of 4 to 6 cm/s at 50 to 90 m. On the east side, inflow extends from a depth of 20 m or shallower down to about 85 to 115 m. Upward slope of this deeper zero level also occurred from west to east, and approximately agreed with the relatively small inflow at the mid-channel Aanderra mooring. The lack of correlation at mid-depths between the two sides emphasizes the uncertainty associated with the mean current profiles at the Aanderaa mooring between the 24-m and 114-m instruments (Figure 32).

At the Admiralty Inlet reference mooring, the channel near bottom is more east to west, and the flow follows the channel before turning southward (Figure 2). The Aanderaa meters were near the bottom and always showed inflow through the narrow, deep channel (Figures 32-33). Net inflow speeds exceeded 15 cm/s during these two deployments, but were as large as 42 cm/s in other deployments.

4.0 DRIFTER OBSERVATIONS

Current meters measure flow at fixed locations, while dye, drogues and drift cards measure flow by traveling with the water. The contrast between these two different ways of observing water motion provides a useful tool for understanding circulation in the Triple Junction.

4.1 Drift Cards

Overall, beachcombers reported 2,702 cards (as of May 14, 2002), or 44.3% of the 6,100 total cards dropped during this study. Of the total reported, 59 cards (2%) were reported without specific positions, leaving 2,643 cards usable in further analyses. These percentages are comparable to drift card studies previously carried out in the Pacific Northwest (Ebbesmeyer and Coomes, 1993; Ebbesmeyer et al., 1995; Ebbesmeyer et al., 1998a; Ebbesmeyer et al., 1998b).

Table 6 lists the dates of each release and the number of cards deployed at each site. During releases 1-9, 400 cards were dropped at sites 1-8, whereas during releases 10-14, 500 cards were dropped at sites 9-18. Table 6 also lists the percent reported within two weeks after release and the total number reported.

Results from releases 1 to 9 and releases 10 to 14 are discussed separately, as the first nine releases were dropped over a larger geographic area than the subsequent five releases. In all cases, the region was separated into three recovery zones: Puget Sound, Admiralty Inlet and the Strait of Juan de Fuca. The areas were defined as follows: Puget Sound, inland of latitude 47°56'N; Admiralty Inlet, between 47°56'N on the south and the line connecting Point Partridge and McCurdy Point on the north and; Juan de Fuca Strait, seaward of the northern boundary of Admiralty Inlet.

The drift card results were displayed in two ways: where they were found and where they originated. The locations drift cards were reported found are shown in Figures 34 and 35 for releases 1-9 and 10-14, respectively.

Where-From maps for collection zones in the vicinity of Meadow Point, Point Wells, Edwards Point, Picnic Point and Point Jefferson are discussed later in this report.

4.1.1 Seasonal Cycle of Drift Card Recoveries

Table 6 lists the percent of each release recovered in Admiralty Inlet and the Strait of Juan de Fuca. In releases 1-9, there is possibly a seasonal cycle with maximal recoveries in Admiralty and beyond during the winter period. This cycle was not particularly evident during releases 10-14, but may have contributed to the lower overall return rate by carrying more cards out towards the Pacific Ocean.

Releases 1-9

Overall, beachcombers reported 2,038 cards, or 56.6% of the 3,600 total cards dropped during releases 1 through 9. Of these, 52 cards (3%) were reported without specific locations, leaving 1,986 cards usable in further analyses. Figure 4 shows most of the drift card reports (approximately 100 were farther west in the Strait of Juan de Fuca). Of the

1,986 reports, 43.8% (869 cards) were found in Puget Sound, 40.9% (812 cards) in Admiralty Inlet, and 15.3% (305 cards) in the Strait of Juan de Fuca (Figure 3). The majority (72.6%) of the cards from each release were reported within two weeks after deployment.

Table 6.
Drift Card Summary

Drift Card Release	Date	Number Deployed	Total % Reported (# cards)	% Reported Within 2 Weeks	% recovered in Admiralty Inlet and beyond (# cards)
1	Aug 28, 2000	400	47.3 (189)	63.0	61.3 (116)
2	Oct 25, 2000	400	49.8 (199)	55.1	43.2 (86)
3	Nov 30, 2000	400	51.3 (205)	80.2	91.2 (187)
4	Mar14, 2001	400	67.8 (271)	77.0	96.7 (262)
5	Apr 12, 2001	400	47.3 (189)	80.3	47.1 (89)
6	Apr 20, 2001	400	68.3 (273)	72.3	17.6 (48)
7	Jun 7, 2001	400	61.5 (246)	81.6	46.3 (114)
8	Jun 7, 2001	400	64.8 (259)	82.4	42.9 (111)
9	Jul 12, 2001	400	51.8 (207)	61.8	38.2 (79)
Sub-totals	August 2000 – July 2001	3,600	56.6 (2,038)	72.6	55.0 (1092)
10	Nov 26, 2001	500	36.6 (183)	73.3	23.0 (42)
11	Dec 21, 2001	500	22.6 (113)	79.8	33.6 (38)
12	Dec 22, 2001	500	22.6 (113)	63.2	16.8 (19)
13	Dec 26, 2001	500	26.6 (133)	71.2	54.9 (73)
14	Dec 27, 2001	500	24.4 (122)	70.3	65.6 (80)
Sub-totals	November-December 2001	2,500	26.6 (664)	71.6	38.3 (252)
Totals	August 2000 – December 2001	6,100	44.3 (2702)	72.1	50.9 (1344)

Table 7 shows the percentage of cards released at a given site and reported within the three general regions. Elevated percentages (greater than 50%) extend from south of Point Wells to Possession Sound. The inshore-offshore difference is largest off Possession Sound (sites 1 & 2) where 55% of the cards from the inshore site were found within the Main Basin and Possession Sound compared with 35% from the offshore site (Table 7). At the release site off Browns Bay, 50% to 60% of the cards were found inland of Admiralty Inlet compared with 30% to 40% in Possession Sound and off Carkeek Park.

During drouge deployment B, drift cards were dropped with a drogue at each of the drift card release sites. For this comparison, the drogue was used in surface-drift configuration (approximately 1 m depth; no sail used) and tracked for a day. Three of the four inshore drogues (at sites 2, 4, 8) beached on the shores closest to their release sites. The drogue from Site 1 also beached in the same area as that from Site 4, but the remaining drogues generally headed toward Admiralty Inlet (see Section 4.2).

Of the 869 drift cards that were reported found within Puget Sound, 390 cards (45%) were found along the eastern shore between West Point northward to Possession Sound and 12% (101 cards) in the vicinity of Point Jefferson. This tally of 491 cards was subdivided into five collection zones (organized by decreasing order of cards):

34% (168 cards) Edwards Point;
 21% (101 cards) Point Jefferson;
 18% (91 cards) Meadow Point;
 17% (82 cards) Point Wells;
 10% (49 cards) Picnic Point.

Table 7.
Regional Drift Card Summary

Release site	Percent of recoveries in Main Basin & Possession Sound (# cards)	Percent of recoveries in Admiralty Inlet (# cards)	Percent of recoveries beyond Admiralty Inlet (# cards)
1 Offshore, Possession Sound	28% (73)	52% (135)	20% (53)
2 Inshore, Possession Sound	50% (106)	38% (72)	12% (26)
3 Offshore, Browns Bay	54% (115)	29% (62)	17% (37)
4 Inshore, Browns Bay	60% (177)	24% (71)	15% (45)
5 Offshore, Point Wells	35% (89)	57% (145)	8% (21)
6 Inshore, Point Wells	55% (140)	29% (73)	16% (41)
7 Offshore, Carkeek Park	28% (68)	52% (124)	20% (47)
8 Inshore, Carkeek Park	39% (101)	47% (120)	14% (35)
Subtotals 1-8	44% (869 cards)	41% (812 cards)	15% (305 cards)
9 Farthest off Edmonds	73% (77)	16% (17)	11% (11)
10 Mid site off Edmonds	68% (66)	25% (24)	7% (7)
11 Closest to Edmonds	64% (46)	15% (11)	21% (15)
12 Farthest off Edwards Pt	29% (27)	56% (51)	15% (14)
13 Mid site off Edwards Pt	42% (15)	22% (8)	36% (13)
14 Closest to Edwards Pt	52% (28)	26% (14)	22% (12)
15 Mid site north	79% (45)	9% (5)	12% (7)
16 Farthest off Pt Wells	35% (11)	39% (12)	26% (8)
17 Closest to Pt Wells	58% (41)	23% (16)	19% (13)
18 Mid site south	53% (23)	19% (8)	28% (12)
Subtotals 9-18	58% (379 cards)	25% (166 cards)	17% (112 cards)
Overall % Recovered	47% (1248 cards)	37% (978 cards)	16% (417 cards)

To understand the origins of the cards found in the collection zones, Figures 36 through 45 showing how many cards arrived at a particular collection zone from each drift card release site. These backward-in-time maps are referred to as the “Where-from” maps, whereas the forward in time maps are referred to as the destination maps. Figures 36 through 40 show the origins of cards arriving at five concentration zones (south to north; east to west) from Releases 1-9: Meadow Point; Point Wells, Edwards Point, Picnic Point and Point Jefferson. These are described as follows:

Meadow Point Zone (Figure 36). Of the 91 cards found in the Meadow Point collection zone, 90% arrived from the inshore release sites off Point Wells and off Carkeek Park. Most of the arrivals originated from off Point Wells (51% or 46 cards).

Point Wells Zone (Figure 37). Of the 82 cards found in this shoreline segment, 50% originated from the releases immediately offshore (Pt Wells Inshore release site).

Edwards Point Zone (Figure 38). Of the 168 cards found in the Edwards Point Zone, most (65%) originated from the inshore site immediately adjacent to this Zone (Release Site 4), followed by 26% from offshore Site 3.

Picnic Point Zone (Figure 39). Of the 49 cards found in this Zone, most (55%) originated from the inshore sites near the northern and southern ends of this Zone (Release Sites 2, 4), followed by 33% from the offshore sites (1, 3).

Point Jefferson Zone (Figure 40). Located along the western shore of the study area, Point Jefferson received the second highest number of cards following the Edwards Point Zone. Of the 101 cards found in this Zone, 34% originated from off Point Wells, 29% from off Browns Bay, and 34% from Possession Sound.

Releases 10-14

Beachcombers reported 664 drift cards, or 26.6% of the 2,500 total cards dropped throughout the winter during releases 10 through 14. Of the total reported, 7 cards (1%) were reported without specific positions, leaving 657 cards useable for the analyses. The majority (71.6%) of which were reported within two weeks after deployment. Of the 664 cards reported, 58% (379 cards) were found in Puget Sound, 25% (166 cards) in Admiralty Inlet, and 17% (112 cards) in the Strait of Juan de Fuca (Table 7).

The release sites were grouped into three regions: sites 9 through 11 were 1 km North of Edwards Point, sites 12 through 14 were off of Edwards Point, and sites 15 through 18 were off of Point Wells (Figure 3). 59% of the recovered cards dropped off of Edwards Point were found outside of the Main Basin, in Admiralty Inlet and the Strait of Juan de Fuca (Table 6). Following Edwards Point was Point Wells with an average of 43.5% and the region 1 km north of Edwards Point with an average of 31.7%. Relatively few cards were found in the five collection zones described earlier within Puget Sound (Figs 41-45). Beachcombers reported 14 cards at Point Jefferson, 2 at Picnic Point, and none at Edwards Point, Point Wells and Meadow Point.

In comparison to Releases 1-9 where a high percentage (45%) of cards were found along the eastern shoreline of Puget Sound, only 0.5% (2 cards) of the cards found within Puget Sound were reported along the eastern shoreline (Figures 41-45). The cards were primarily concentrated in the vicinity of the southern entrance to Admiralty Inlet, with 31.4% (119 cards) found on the southern tip of Whidbey Island.

Additionally, there was a decrease in the percentage of cards found at Jefferson Point from 12% of the total cards found in the Main Basin during releases 1 through 9 to 4% during releases 10 through 14 (Figure 45). Despite the decrease in the number of cards found at this collection zone, the origin of these cards supports previous observations made during releases 1 through 9 and continues to reflect westward movement across the Triple Junction followed by southward movement in the Kitsap counter current.

The position of Site 16 was chosen to duplicate the position of Site 5 to provide continuity with the Phase 2 releases. Cards reported that originated from Site 16 were found to reflect a dispersal pattern similar to that of Site 5. During both release periods, cards tended to accumulate at Point Jefferson, along Admiralty Inlet, and in the Strait of Juan de Fuca.

4.2 Drogues

Drogue trajectories reflect tidal currents and the low-frequency modal currents, and the resulting trajectories often resemble neither the tides, prevailing flow, intrusions, or wind induced flow, but rather a complex blend of all four.

Drogue observations were used to integrate the arrays of current meter measurements into circulation patterns within the Triple Junction. Trajectories from multiple releases at the same location showed that within a week the drogues could end up almost anywhere in the Triple Junction. One puzzling aspect was that no deep drogues were observed to enter Possession Sound, although mean currents indicated a persistent inflow at these depths. The weeklong deployments showed flow patterns that exhibited a wide range of behavior and varied substantially from those characteristic of the general mean flow (Figures 10-13).

Drogues were deployed in groups of 3 to 7 on 18 occasions, and a total of 106 drogues were tracked for 69 days (Table 4). The following discussion includes representative patterns that can be partly explained by different physical processes. Most of these variations appeared to be caused by wind effects that are further discussed in Section 5.4. The trajectories are described in several ways: those with particularly interesting paths; composites released in the vicinity of proposed outfall sites; and calculations of selected trajectories. The overall impression conveyed by the five composites is that within a week, drogues released off Point Wells and Edwards Point may travel almost anywhere in the Triple Junction. Drogues above approximately 30 m may travel across the Whidbey and Jefferson shoals. One drogue (G3 at 125 m; Figure 54) traveled westward then inland.

Groups of drogues released during a day to a week under selected environmental conditions (winds, tides, intrusions, river discharge). The associated trajectories reflected the particular blend of those conditions. Effluent, however, will be released continuously and will reflect a wide range of such conditions. For this reason, drogues released in the vicinity of the same area where outfalls were considered were superimposed to provide a view of overall effluent dispersion.

Figures 46-48 present the superposition of drogue trajectories from releases off Point Wells at three depth ranges (8-25; 55-75; 105-125 m). Drogue trajectories from releases off Edwards Point at two depth ranges (55; 125-155 m) are shown in Figures 49-50. These composite trajectories are comparable to the maps of currents at 20, 60, and 100 m, and at 60 and 140 m, respectively (Figures 10-13). In these composites 44 of 106 drogues were used (Table 8).

Drogue Deployment B

Figure 51 shows drogue trajectories for one day in late-August 2000. Eight drogues were released at the surface (no subsurface sails) simultaneously with the first drift card deployments at all eight sites. The drogues were released on a large ebb current. Half of the drogues grounded before the end of the tidal day. Three of the four that grounded were

released at the sites closest to shore. Of the four released north of Edwards Point, three grounded north of Edwards Point. This is the region of converging and diverging of flood-tide currents discussed later in Section 5.3. The offshore drogue in Possession Sound appeared to follow these currents and grounded in the divergence zone north of Edwards Point. The one drogue north of Edwards Point that did not ground was released at the same offshore site as the one drogue that escaped this region in Deployment D.

Drogue Deployment D

Figure 52 shows trajectories for drogues tethered at 20 to 30 m and released at seven of the eight drift card sites for six days in October 2000. The sites were near shore and offshore off Meadow Point (gold, green), Point Wells (none, blue), Edwards Point (pink, black), and Possession Sound (yellow, orange), respectively. The near-shore drogue off Point Wells failed to transmit. All but one of the trajectories (black) showed long excursions along the shore, and most of these (except gold) extended into Possession Sound. Three of the drogues (gold, blue, pink) reversed direction in Possession Sound, and flowed south near the shore. The two drogues released off Possession Point at the southern entrance to Possession Sound (yellow, orange) did not reverse, but drifted into Port Susan. One of these lost its sail at an unknown time. The gold trajectory grounded off Edmonds.

The offshore drogue at Edwards Point (black) had a completely different trajectory that extended out Admiralty Inlet. It apparently was entrained into the mean outflow shown in Figure 10 that may be part of a flow convergence of Possession Sound and Main Basin waters.

The drogues at 20 to 30 m that flowed into Possession Sound may have been trapped near shore by winds blowing from the south that intensified the near-shore currents. Time series of filtered (tides removed) along-channel currents at 2 and 24 m at the Possession Sound Aanderaa mooring and of the along-channel component of winds showed high correlation between the winds and 2-m currents (Cannon et al., 2001). Winds from the south (generally associated with storms) significantly reduced the surface outflow, and sometimes reverse it. The effect of winds on the circulation of Possession Sound and the Main Basin is discussed in Section 5.2.

This deployment occurred near the end of current meter Deployment 2 at the beginning of a northward flow into Possession Sound at 24 m (Cannon et al., 2001). The flow at this depth, near the depth of the drogues, reversed direction numerous times. This depth is the approximately long-term level of no-net-motion (Figure 32), and oscillations of the no-net-motion level above and below the mean disguise the substantial extent of the intrusions to the north and south. The inflow started the day the drogues were deployed reaching a maximum of 2 to 3 cm/s, and it lasted for about four days. The speeds and durations were sufficient to produce the observed excursions. The flow reversed to southerly during the rest of the deployment accounting for the reversed flow of the drogues.

Because the depth of these drogues was near the no-net-motion level of the mean current profiles, the effects of the winds may be harder to determine. But, flow at this level can have significant excursions into Possession Sound, and it is difficult to relate these patterns to the low frequency currents. Thus, it is important to understand the time variations of the tidally averaged currents that seem to produce a northward near-shore flow. The northward intrusion process is shown later to have a maximum near mid-depths, and winds cause an oscillation opposite to the surface flow.

Drogue Deployment F

Deployment F in January 2001 released shallow (50-60 m) and deep (120-130 m) drogues at four sites from Edwards Point to Possession Sound. Two locations coincided with offshore drift card sites; the other two locations were halfway between offshore drift card sites. Figure 53 shows the trajectory of the 120-m drogue released at the drift card site south of Browns Bay. The drogue initially drifted across the Main Basin similar to the shallow drogues during Dye Study 1 (see below). It then flowed south along the Kitsap Peninsula to Point Jefferson, drifted westward across Puget Sound, and returned northward to Point Wells. The circuit around the Main Basin is repeated a second time. During the second westward excursion, there is an oscillating pattern caused by the tidal currents. Winds during the beginning of the deployment were from the north and are thought to have augmented the initial southwestward cross-channel flow.

The cessation of southward flow off Point Jefferson is probably caused by convergence with mean flow from farther south. Flow at 100 m off Meadow Point is all southward (Matsuura and Cannon, 1997). Somewhere off Point Jefferson, the 100-m mean flow becomes northward as it turns on the eastern side of the basin to flow along Point Wells at that depth. Thus, the flow at that level can travel around the Main Basin or converge with the inflow from Admiralty Inlet (Figure 18) and flow toward and into Possession Sound (Figure 8). However, the observations here did not reveal where this occurs.

Drogue Deployment Dye Study 1

Figure 54 shows drogue trajectories during the Dye Study 1 experiment in February 2001. Eight drogues were released at a depth of 3 to 13 m off Browns Bay at approximately hourly intervals during a large ebb and then large flood tide. The drogues stayed near the deployment site for about 12 hours. Then they drifted southwesterly along shore and across channel from Edwards Point to the Kitsap Peninsula. There, about half flowed north along shore, and the other half drifted south to the vicinity of Point Jefferson. Near Point Jefferson, two of the drogues rounded the point and headed a little west toward the area where drift cards released from off Point Wells were found (Figure 34). Two of the four northward flowing drogues went out Admiralty Inlet into the Strait of Juan de Fuca, the third grounded at the north end of Admiralty Inlet, and the fourth probably was caught in a ship tow and dragged into Possession Sound.

This drogue deployment occurred during current meter mooring Deployment 4. Winds measured at Paine Field during the initial deployment were southerly (to the north) followed by two days of intense north winds. The south winds probably kept the drogues trapped, and the following relaxation of wind allowed the drogues to flow across Puget Sound. In a later section on wind effects (Section 5.2), it can be seen that Browns Bay is located approximately at a divergence of flow caused by southerly winds. It is also shown that wind effects on currents at 20 to 40 m in the region north of Edwards Point are opposite to the wind direction. That is, north winds augment northeast flow north of Edwards Point, and south winds augment southwest flow. Further study is needed to determine this difference at the sea surface. It also is uncertain why the drogues did not show some sort of tidal oscillation as they crossed the Main Basin, and why they diverged when they arrived at the Kitsap Peninsula.

Student Projects

Drogues released by two students in the University of Washington Oceanography 460 class followed the general mean flow shown in Figure 1. The first set drifted along the Main Basin from Colvos Passage and into Admiralty Inlet (Hoglund, 2001), and the other set drifted from Possession Sound, over the Whidbey shoal, and into Admiralty Inlet (Burcal, 2001). Drogue trajectories are shown in Appendix F.

Table 8.
Drogues Included in Composites

Release site for composite: depth range	Number of drogues in composite	Drogue Releases
Edwards Point: 55-75 m	12	F, G, H, I, Dye 5
Edwards Point: 125-155 m	4	F, G, H
Point Wells: 1-25 m	10	B, D, E, Dye 2, Dye 4
Point Wells: 55-75 m	15	G, J, K
Point Wells: 105-125 m	3	E, G
Total	44	

4.3 Dye Releases

Dye studies were conducted during the weeks of February 5, March 12, May 7, and June 5, 2001. A fifth study was conducted the week of February 4, 2002. The February and May 2001 injection sites were in Browns Bay vicinity, and the March and June 2001 injection sites were in the Point Wells vicinity. The February 2002 injection site was in the vicinity of Edwards Point. In each study, dye was injected from shortly after a high or low water stand through the following high or low water stand. The first four injections occurred during large ebb and flood tides to examine the maximum tidal excursion distances. The fifth study occurred during a minor flood and ebb cycle. Comprehensive presentation and discussion of the dye study results is provided in Appendix G. The following paragraphs summarize the key findings of the five dye releases:

Study 1 – Browns Bay Shallow Injection

The first dye injection began at 1655 on February 5 and ended at 0520 on February 6, 2001. The dye injection station was moored in the Browns Bay vicinity at 73 m. The diffuser was set at 5 m at the top and 11 m at the bottom. A total of 44.9 kg of Rhodamine WT dye was injected at a rate of 1.00 g/s over one semi-diurnal tide cycle.

The study was dominated by heavy northwest winds that set in immediately after the dye injection was complete. The strong winds forced suspension of the manual shoreline sampling on the second day of the study. It also raised turbidity in waters along the shorelines, which raised the background dye recordings to approximately 0.04 ppb, which may have masked dye that may have reached some of the stations.

The only dye contact with the shorelines stations was to the south (downwind) of the injection site. Trace concentrations on the order of 0.1 to 0.2 ppb were observed at the County Park and Ocean Avenue stations before the wind rose on the morning of Day 2. Similar concentrations were observed later in Day 2 at the Meadowdale and Edmonds autosampler locations, which were the only stations recording during the Day 2 windstorm. No significant dye concentrations were observed on subsequent days at any of the monitoring sites with the exception of the Edmonds station.

Study 2 – Point Wells Shallow Injection

The second dye injection began at 0715 on March 12 and continued through 1938. The dye injection station was moored off Point Wells at 79 m. The diffuser was set at 5 m at the top and 11 m at the bottom. A total of 50.2 kg of Rhodamine WT dye was injected at a rate of 1.13 g/s.

As with the first study, winds again affected the sampling program. Strong southerly winds set in at the conclusion of the dye injection system and continued into Day 2. The winds forced suspension of the manual sampling stations between 1730 on March 12 until 0700 on March 14.

Only the Edmonds and Edwards Point autosamplers were online during the last part of Day 1 and through Day 2. Both stations saw brief pulses of dye early on March 13 (approximately six to eight hours after the dye ended), with concentrations approaching 0.2 ppb. There were no detections at any stations after these measurements.

Study 3 – Browns Bay Deep Injection

The third dye injection began at 0530 on May 7 and ended at 1800. The dye injection station was moored in the Browns Bay vicinity at 126 m. The diffuser was set at 22 m at the top and 28 m at the bottom, which were substantially deeper than the first two studies. A total of 48.1 kg of Rhodamine WT dye was injected at a rate of 1.07 g/s for one semi-diurnal tide cycle.

Weather cooperated during this study and all stations were fully sampled for over four complete days. The lack of strong winds resulted in lower turbidity at the shoreline, which lowered the background concentrations to approximately 0.02 ppb.

All of the shoreline stations from the injection site north observed dye, while none of the stations to the south of Browns Bay. Peak concentrations were on the order of 0.4 ppb, and generally occurred near the end of the dye injection and late morning of Day 2. Trace concentrations were observed on Day 3. Figure 55 shows the time series of dye concentrations measured at the Meadowdale Marina shoreline station.

Study 4 – Point Wells Deep Injection

The fourth dye injection occurred between 0450 and 1840 on June 5, 2001 during a large ebb and flood cycle. The dye injection station was moored off Point Wells at 190 m. The diffuser was set at 22 m at the top and 28 m at the bottom, the same as Study 3. A total of 51.1 kg of Rhodamine WT dye was injected at a rate of 1.03 g/s.

All of the shoreline stations were fully sampled for 3.5 days according to the study plan. Winds were light, which again held the background fluorescence to approximately 0.02 ppb.

Only the stations north of the injections site observed any dye. Figure 56 shows the time series of dye concentrations measured at the Edmonds station. The dye injection period, tide and estimated background concentration are also shown. Peak concentrations were less than 0.1 ppb and occurred near the end of the dye injection period. Lower concentrations with longer durations were observed on Days 2 and 3 at several stations north of the injection site.

Study 5 – Edwards Point Deep Injection

The fifth dye injection occurred from 1440 February 4 through 0300 February 5, 2002, during a minor flood and ebb cycle. The dye injection station was moored off Edwards Point at 171 m. The diffuser was set at 55 m at the top and 61 m at the bottom, which was substantially deeper than the previous studies. 95.5 kg of Rhodamine WT dye was injected at a rate of 2.15 g/s.

Study 5 had the deepest of all of the dye injections, and the dosage was doubled from the previous studies. The dosage was doubled because of the low concentrations anticipated at the shallow shoreline stations.

None of the shoreline field samples exceeded the RDL of 0.04 ppb during this study. Over 95 percent of the results were below the MDL of 0.02 ppb. Therefore, there is no indication of any shoreline contact of dye injected at the Edwards Point deep station.

5.0 ANALYSES AND DISCUSSION

This section assesses tidal divergence and convergence, flow variations created by winds and intrusions, and various flow patterns observed within the Triple Junction and Main Basin. Seasonal and long-term climatic changes are discussed as observed in the current meter data set and the available historic data. The current observations have been synthesized into mean flow and variability schematics. These analyses are intended to put the observations for King County in a broader perspective. They also can provide direction for planning further analyses of these observations and future oceanographic field measurements.

5.1 Tidal Currents

The tidal currents depicted in Section 3.2 dominate the flow within Puget Sound. Tidal ellipses provide an alternative method to analyze and depict time series of current velocities. This method represents the current time series by a mean velocity plus a number of sinusoidal harmonic terms, each representing a component of the gravitational tide. The harmonic terms are known as tidal ellipses since each term represents a particular frequency of the tide and the sinusoidal representation of north-south and east-west current speed traces an elliptical shape. Practically, this method decomposes the current record into Fourier components corresponding to the major tidal frequencies. Each component is the best fit to the velocity fluctuations at the corresponding tidal frequency. The resulting ellipses provide a convenient method of visualizing the spatial variation of tidal currents, as well as the relative contribution of each tidal harmonic and the mean current speed. This approach does not describe the low-frequency variability observed in the observations (Section 3.3) since the current variability is assumed to be entirely tidal in nature.

A current time series, composed of u (positive toward east) and v (positive toward north) components of velocity, is decomposed into sinusoidal terms as

$$u = a_u \cos(\omega t + \theta_u),$$

$$v = a_v \cos(\omega t + \theta_v),$$

where ω is the tidal frequency.

As described above, the tip of this velocity vector traces an elliptical shape. The shape of this ellipse can also be described by the length of its major and minor axes and the orientation of the ellipse. Seven tidal harmonics were selected to represent the tidal currents based on their relative size (Table 9).

The velocity time-series from each ADCP current meter was averaged vertically through a given depth range, typically 20 m, to create a single time series. This time series was then fit by least-squares regression to obtain the Fourier coefficients and phases. The resulting sinusoidal velocity components were transformed to obtain the major and minor semi-axes of the ellipse, and the angle of inclination of the major axes to the east. The mean current is obtained as the constant Fourier coefficients.

Table 9.
Tidal Harmonics and Associated Periods

Tidal Harmonic	Period (hours)
M2	12.421
K1	23.934
S2	12.0
N2	12.658
O1	25.819
P1	24.066
M4	6.210

The tidal ellipses are visualized graphically in Figures 57 through 60, which show the M2 and K1 tidal ellipses for the depth ranges of 20-40 m and 100-120 m. Figures 57 and 58 illustrate these ellipses for the M2 tidal component, while Figures 59 and 60 show the K1 tidal component. In these figures, the red dot represents the current meter location, with the mean current vector shown in red from this location. The current ellipse is then drawn about the end of the mean current vector. Tidal ellipse constituents are in Appendix K.

At most locations and depths, the velocity record is dominated by the M2 tidal component. This is characteristic of the tides within Puget Sound. The most energetic tidal regions are immediately to the south of Admiralty Inlet south to the vicinity of Point Wells.

The orientation of the tidal ellipses tends to align with the bathymetric features, predominately in a north-south alignment. The current ellipses offshore and north of Edwards Point rotate as the flow curves around Whidbey Shoal. The rotation of the tidal ellipses occurs further south at greater depths, indicating the effect of the shoal. Outside of this region, the tidal ellipses do not vary significantly throughout the water column.

Previously, McGary and Lincoln (1977) investigated the tidal flows within Puget Sound using a physical model. This model, located at the University of Washington (UW), was found to accurately represent tidal currents near the surface, based on comparisons with numerous field measurements. However, the model is limited in that it does not reproduce wind or rotational effects, and surface tension decreases its accuracy near the shore. Flow patterns at deeper depths in the model were not determined except for the general along channel bottom flow.

Figure 61 shows surface tidal flow patterns from the UW model during a large ebb tide, a large flood tide and at slack after a large flood tide (McGary and Lincoln, 1977). These flow patterns were obtained from time-lapse photographs of surface tracers. During ebb tide in the region between Picnic Point and Edwards Point, the model shows a convergence of currents from Possession Sound and the Main Basin that then flows across the Whidbey Shoal. During flood tide in the same region, the flooding current crosses the shoal, impinges on the shore between the same points, and then divergences north and south. There appears to be a stagnation region in the vicinity of Browns Bay. During high water after flood, commonly called slack water, there are eddies and cross-channel flows. Overall, these tidal patterns closely resemble the observed tidal currents at 20 m (Section 3.2, Figure 6).

The tidal ellipses show the divergence/convergence area off Browns Bay as suggested by the UW model and tidal current directions obtained from the current meters. The M2 phases at moorings 5 and 12 point in opposing directions, and Mooring 11 shows the resulting onshore-offshore flow from this divergence/convergence.

Table 10.
Semi-Major axes of M2 and K1 Tidal Ellipses at 60m

Meter	M2 Semi-major axis (cm/s)	K1 Semi-major axis (cm/s)	Meter	M2 Semi-major axis (cm/s)	K1 Semi-major axis (cm/s)
Deployment 1			Deployment 5		
1	19.4	11.2	29 ^a		
2	22.4	7.8	30	33.4	8.3
3	17.0	6.4	31	32.1	15.6
4	13.8	4.5	32	30.4	14.1
5	11.8	3.3	33 ^a		
6	19.0	6.4	34 ^a		
Deployment 2			35	15.6	2.8
7	26.0	12.7	36	26.5	11.0
8	31.6	12.2	Deployment 6		
9	26.1	8.8	37	14.4	6.2
10	14.1	6.1	38	16.0	6.9
11	7.4	3.3	39 ^a		
12	4.3	1.6	40 ^a		
Deployment 3			41	20.8	9.1
13	13.8	6.8	42	14.2	6.8
14	13.0	7.4	43	9.4	4.4
15 ^a			Deployment 7		
16	11.1	4.3	44	26.5	11.0
17	8.3	4.1	45	6.9	3.6
18	9.9	4.6	46	23.4	10.4
Deployment 4			47	6.7	5.7
19	13.1	1.6	48	11.4	4.8
20	17.4	5.5	49	20.9	4.6
21	21.2	7.5	Deployment 8		
22	22.6	7.4	50	19.1	6.4
23	23.1	7.8	51	13.8	6.5
24	22.8	6.2	52	9.2	4.1
---	---	---	53	18.4	6.8

^a – Meters deployed at depths less than 60m

The tidal flow pattern at high water shows a westward flow north of Edwards Point that crosses the Main Basin to the Kitsap Peninsula where it diverges north and south toward Point No Point and Apple Cove Point, respectively. This pattern appears similar to the drogue trajectories from the Dye 1 drogue release (Section 4.2). It may also suggest the mechanism by which the drift cards may have moved west before eventually washing ashore near Point Jefferson.

A UW student project (Kende, 2001) associated with this study measured currents with an underway shipboard ADCP. Four sets of observations, two each during ebb and flood currents, were made around a triangular path above the Edwards Point moorings (1-5) and Edmonds moorings (7-12) (see Section 2.1). Clearly defined ebb and flood currents were shown along the southern leg above moorings 1-5 and the northwestern leg above moorings 7-9 (Figure 62). However, along the track above moorings 9-12 the flow was more nearly parallel to the track. This observation suggests that the flows along this track are often onshore/offshore, a result that is also seen in observed tidal currents, particularly at 60 m (Figure 7), and in the flow patterns from the UW physical model (Figure 61).

Tidal Influence on Drogue Trajectories

Figures 63-65 show drogue trajectories that are color coded to show where they were dominated by the tidal currents in the Main Basin or in Possession Sound, or by neither. To determine these effects, time series of currents were created for each of the drogues assuming it was at a fixed location. The drogue currents were compared with currents at the Aanderaa reference moorings in the Main Basin and Possession Sound. Drogue tracks in red had visual correlation with Main Basin currents, and blue, Possession Sound currents. Drogue tracks in green did not correlate with either current system, and all these cases occurred between Edwards and Picnic points with the dominant concentration just south of Browns Bay.

Figure 63 shows trajectories during Deployment E of the four shallower drogues at about 25 m at the four offshore drift card sites. The two drogues deployed in the Main Basin ended up near Kitsap Peninsula. The Possession Sound drogue flowed into the convergence region and grounded off Browns Bay. The drogue deployed on the convergence region flowed to Whidbey Shoal and through the canyon into Admiralty Inlet.

Figure 64 shows trajectories during Deployment F of drogues deployed at about 55 m at four sites from Edwards Point to Possession Sound. All trajectories ended up in the convergence region, and one continued up the canyon onto Whidbey Shoal and into Admiralty Inlet. A deeper drogue deployed at the same time at 125 m in the convergence region behaved completely differently. It traveled southward into the Main Basin and made two circuits around the recirculation feature between Whidbey and Jefferson shoals (Section 4.2, Figure 48).

Figure 65 shows trajectories during Deployment E of the four deeper drogues at about 105 m at the four offshore drift card sites. The three northernmost drogues illustrate the mid depth convergence off Browns Bay. The drogue from Point Wells flowed north, and the drogue 2 from Possession Sound, south. They meet and flow northward with the middle drogue, until they all bumped into Whidbey Shoal (50 m shaded). It is postulated that this deeper water could be raised hydraulically to flow up and over the shoal. Drogues cannot do that; they are dragged around the shoal by the surface floats attempting to follow the surface outflow. The southern most drogue remained in the Main Basin. It initially flows

south, then flows north and makes one circuit around the recirculation feature north of Point Jefferson, and ends in an eddy south of Point Jefferson.

The convergence flow in the UW hydraulic model is in the approximate location of the path of the shallow black drogue in Deployment D (Section 4.2, Figure 47). Assuming the general tidal flow pattern extends to the bottom, this convergence provides some confirmation how the deep drogues in Deployment E ended up at Whidbey Shoal (Figure 65). Similarly, the divergence flow during Deployment Dye Study 1 may have stagnated the drogues in Browns Bay, and the subsequent cross-channel flow at high water augmented the cross-channel flow of the drogues (Section 4.2, Figure 49). However, the tidal characteristics shown by the model represent only a few hours, and other forcing functions are necessary to fully explain the longer duration of the drogue trajectories.

Figures 63-65 are near depths of 25, 55, and 105 m, approximately the same as 3 of the 4 depths of the tidal current maps from the moored current meters (Figures 6-8). However, the drogues do not show the southward shift in the convergence zone that is evident in the tidal current maps, but they do show the convergence spread over the entire region from Edwards Point to Browns Bay. This region appears to be one of highly variable and confused flow, sometimes influenced by the Main Basin and sometimes by Possession Sound.

5.2 Wind Effects

There are two major forces, winds and bottom water intrusions, that can cause significant variations about the mean estuarine circulation (described by Bretschneider et al., 1985), and the magnitudes of these low-frequency variations can be as large as the mean currents (Figures 10-13). This section discusses the effect of wind forces on the circulation and the effect of bottom water intrusions is discussed in the next section. Winds in the direction of the surface flow augment it, and winds in the opposite direction impede and sometimes reverse the surface flow. The effects at the surface require compensating flows at depth (opposite direction), or there would be an accumulation or a draining of water from Puget Sound. Previous studies in the Main Basin showed that compensating flows occurred at mid-depths around 100 m (Matsuura and Cannon, 1997; Ebbesmeyer and Cannon, 2001). There are no prior studies in Possession Sound. The predominant winds over Puget Sound are southerly during storms (blowing to the north) and northerly during periods of good weather (blowing to the south). However, winds cause opposing effects in the Main Basin and Possession Sound because the surface currents in the two branches flow northward and southward, respectively (Figure 6).

Figures 66 and 67 show sample time series of currents and winds at the Aanderaa current meter reference moorings in Possession Sound (November-December 2000) and in the Main Basin off Point Wells (January-March 2001). Vertical profiles of the mean currents at these locations were discussed in Section 3.5 (Figures 32-33). In Possession Sound the winds and 2-m currents appear to be well correlated (Figure 66). Strong winds from the south (> 4 m/s, generally associated with storms) significantly reduced the surface outflow, and even reversed it for one to four days on five separate occasions. During most of this record, currents at 24 and 114 m are negatively correlated with each other. The current at 24-m tends to be in the same direction as the surface flow for much of this record. However, at the beginning of the time series, the 24-m flow is opposite the surface flow. The 114-m flow is mostly directed into Possession Sound, opposite to the surface flow.

Flow at this level weakens and sometimes reverses for about a day, apparently compensating for the reversing current direction at 24 m, that generally coincides with strong winds from the south. The bottom flow at 211 m has alternating inflow and outflow. This deep inflow could be bottom-water intrusions from Admiralty Inlet that partly propagate up Possession Sound (Cannon, 1975), although the corresponding salinity observations did not show a significant concurrent increase.

Figure 67 is a similar time series at the Main Basin reference mooring during February to March 2001. The top panel shows that 2-m currents and winds are not as highly correlated as in Possession Sound. This may be an effect of the wind observations being farther away from this mooring. The bottom panel shows the low-frequency filtered currents at 6 depths. It appears that the flow near the surface and at deeper depths is negatively correlated, with periods of slower bottom inflow corresponding to periods of slower surface water outflow. The flow at 87 m oscillated about zero, typical of the yearlong data record at this mooring, where the level of no-net-motion occurred between 75 and 85 m (Section 3.5). Southerly winds augmented both the surface outflow and the deep inflow at the beginning of the record and in early March. The strong surface current reversal around February 7 may have been due to a short 12-hour period of northerly winds that does not appear in Figure 67 because of the 35-hr filter that was applied. This reversal- reduced both inflow and outflow at other depths to near zero, and could also be a relaxation of the Main Basin after nearly a week of strong southerly winds. Regardless, this time series indicates that compensating flows tend to affect the entire water column. Earlier studies in the Main Basin showed a deep water compensation to surface currents, and the maximum effect occurred nearer mid depths at 100 m (Matsuura and Cannon, 1997; Bretschneider et al., 1985). The sections in these studies were further south off Meadow Point and Three Tree Point, respectively, with levels of no-net-motion shallower than 100 m. It is unclear what effect the sloping level of no net motion observed at the Point Wells section had on these compensating flows. The mooring in Figure 67 was in mid channel where the level of no-net-motion changes rapidly with depth (Figures 15-16).

Figures 68 and 69 are schematic diagrams of the effects of northerly and southerly winds at depths near the surface and near 100 m, respectively. Based on current measurements, a characteristic current vector was plotted for relatively large winds (exceeding about 2.5 m/s or 5 kn) of at least a day's duration, from both the south (red) and north (blue). These figures include results described above for the Main Basin and Possession Sound reference moorings and for several other moorings. In addition to the out-of-phase effects between Possession Sound and the Main Basin, southerly winds off Point Wells strongly augmented the northward near-surface flow. At 100 m, most of the flow reversed, except close to Point Wells where it remained weakly northward because of the deeper level of no-net-motion. Northerly winds decreased the outflow at both levels, except near Point Wells where the already northward flow was augmented.

The flow off Edwards Point is more complicated. It is the interaction region between the currents from and to the Main Basin and Possession Sound. At both depths northerly winds augmented the flow toward Possession Sound, and southerly winds augmented flow toward Admiralty Inlet. Multiple current modes occurred most frequently in this region (Figures 6 and 8).

Figures 68 and 69 suggest that southerly winds cause water at 20 and 100 m to flow southwesterly from the region north and east of Edwards Point. Although the observations in these figures are from different times, they provide a sense of this effect within the

Triple Junction, and they help explain the cross-channel flow of various drifters (shown in Figures 46-54).

Alternatively, northerly winds caused water off Edwards Point to flow northeasterly and converge with the outflow from Possession Sound. This flow pattern may help explain some shallow drogue tracks that escaped to Admiralty Inlet from this region (for example Figure 47). Deep drogues off Edwards Point should also follow this path, but further study is needed to determine what processes affect the trajectories.

5.3 Intrusions

Bottom water intrusions are the second dominant non-tidal forcing mechanism in Puget Sound (described by Bretschneider et al., 1985). Intrusions start during neap tides when mixing in Admiralty Inlet is less vigorous and the maximum amount of salt water is crossing over the sill (first shown by Geyer and Cannon, 1982). Intrusions replace the bottom water in the Main Basin starting first at the Triple Junction. Divergence into Possession Sound and the Main Basin occurs after passing the Whidbey Shoal and seems to be centered on Edwards Point as shown in Section 3.3 (Figure 13). The intrusions propagate down Puget Sound at speeds of about 20 cm/s near the sill and 10 cm/s along the Main Basin (Cannon et al., 1990), and they take about a week to propagate up Possession Sound to the Port Susan sill (Cannon, 1975).

Figure 70 shows the effects of intrusions in a sample time series at the Main Basin reference mooring off Point Wells (Deployment 2, August-October 2000). Tidal currents have been filtered from the observed flow, and the resulting estuarine circulation is a smaller, more slowly varying function of time. The flow at 87 m oscillated about zero, as it did during the Deployment 4 time series discussed in the previous section on wind effects (Section 5.2). The maximum inflows (negative) occurred at 177 m and were accompanied by maximum salinity. Three intrusions at about two-week intervals were centered approximately on September 10, September 24, and October 9, 2000. These intrusions had the maximum salinity that entered the Main Basin at the end of the Pacific coastal upwelling season. During the previous deployment in July and August intrusion salinities began increasing as the coastal upwelling effects propagated into Puget Sound (shown in Figure 81). During the following deployment in November and December, two more relatively large intrusions were observed. Following these events there was a general decrease in salinity associated with the cessation of coastal upwelling, potentially also a result of increased river inflows.

The general salinity pattern observed here was similar to yearlong observations in 1975 through 1976 off Meadow Point (Cannon and Laird, 1978). The 1975 through 1976 observations may have been influenced by onset of an El Nino event (Kawase, 2001, and Section 5.12), which diminished coastal upwelling.

As with wind effects, there also are compensating flows for intrusions. In Admiralty Inlet the increased bottom inflow is accompanied by increased surface outflow, but in the Main Basin compensating outflow occurs at mid depths. Intrusions were observed at 177 m and 147 m (currents and salinity), and compensating flows were observed as increased outflow at 87 m and possibly decreased inflow at 112 m (Figure 70). Thus, intrusions can increase the northward flow near 100 m off Point Wells. If a strong northerly wind (blowing to the south) occurred during an intrusion, there could be combined effects of mid-depth compensating currents, both resulting in enhanced northward flow at 100 m off Point Wells

where the mean flow already is northward. However, in Admiralty Inlet the same northerly winds could decrease both outflow and inflow (Lavelle et al., 1991).

5.4 Low-frequency Currents

In this section selected low-frequency time series and winds are presented for moorings 4, 21, 31, and 32. Explanations of physical processes responsible for selected modal characteristics are illustrated by examining specific events in the time series. It has not been possible in this study to rigorously explain all the events in the time series and phase shifts at the start and end of events, nor has it been possible to explain all of the modal events. Some of the mode descriptions from Section 3.3 are repeated here to put the time series in proper perspective. Explanations of wind and intrusion effects in Sections 5.2 and 5.3, respectively, are directly applicable to the discussion here. Positive currents are northward flow, while positive winds are to the south, called northerly in meteorological notation.

The time series shown here are the low-pass filtered currents. These currents can be further represented as modal currents, as was done to create the low-frequency modal current maps shown in Section 3.3. Here, the modes are identified in the low-frequency time series to assign physical processes to the causes of the modes. Flow corresponding to a particular current mode may be caused by more than one physical processes, and the relative importance of different processes could vary at different times and locations.

Low-frequency Current Time Series: Mooring 4

The temporal variations of the low-frequency (tidally filtered) currents at Mooring 4 off Edwards Point (Figure 2) are shown in Figures 71 and 72 for the northward and eastward directions, respectively. Each figure shows the low-pass filtered current, at 20 meter depth intervals. The north-south component of winds recorded at Paine field, located to the east of Possession Sound, is shown as a solid black line.

Figures 71 and 72 show there was a 6-day period of northerly winds (to the south) centered on 8/1/00, and a period of southerly winds immediately preceded it, centered on 7/27. During the northerly winds the general flow was northward and eastward at all depths. Northerly winds blowing southward through Admiralty Inlet apparently cause the flow at mooring 4, which is north of Edwards point, to flow northeastward. At 20 m this was aligned with the direction of mode 2, and at 60 m, mode 1 (Figures 10-11). During the southerly winds, the flow is northwestward at 20 m and southwestward at 60 m. This corresponds to mode 1 at 20 m and mode 2 at 60 m. Note that at 20 m, mode 2 is stronger than mode 1, although it is less frequent.

Figure 71 shows an intrusion centered on 7/23 that is indicated by the larger southward and westward flows of the deeper water. This is mode 2 at 100 m and mode 1 at 140 m (Figures 12-13).

Three modes are evident at 100 and 140 m. Mode 1 at 100 m follows mode 1 at 60 m during strong winds to the south, and mode 3 occurs as a northward current compensating winds to the north (7/27). At 140 m, mode 2 is southeastward during weaker inflow, but not a major intrusion. Mode 3 appears to be wind caused like mode 1 at 60 and 100 m.

Low-frequency Current Time Series: Mooring 21

The time variations of low-frequency currents at mooring 21, in mid channel off Point Wells (Figure 2), are shown in Figure 73. North-south currents are at 20-m depth intervals, and the north-south winds at Paine Field are shown in black.

Figures 10-13 showed at Mooring 21 that there was one mode at 20 and 60 m (northward) and at 140 m (southward). These are the estuarine outflow at the surface and inflow at depth. Two modes are shown at 100 m (Figure 12). The level of no-net-motion at this location occurs at about 100 m (Figures 15-16). Mode 1 is northwestward flow. Figure 73 shows a large interval of southerly winds centered around 2/2/01 that augments the surface northward flow down to 100 m. Mode 2 is southward flow. Figure 73 shows that it occurred during bottom water intrusions shown by increased bottom inflow around 2/04, 3/04, and 3/16.

Across the Point Wells section two modes were observed at one depth at each mooring (Figures 10-13). They occurred at the deepest level near Point Wells and at the shallowest level near the Kitsap Peninsula. The depths of the occurrences all were near the level of no-net-motion. Multiple modes at the shallower levels most likely were wind induced, and at the deeper levels, intrusion induced.

Low-frequency Current Time Series: Moorings 31 and 32

The time variations of low-frequency currents at Moorings 31 and 32, located in the middle and eastern side of Admiralty Inlet (Figure 2), are shown in Figures 74 and 75. North-south currents are plotted at 20-m depth intervals, and north-south winds at Paine Field are shown in black.

Figures 10-13 showed that there was one mode at 20 m at Mooring 31 and at 100 and 140 m at Mooring 32. These correspond to the estuarine outflow at Mooring 31 and inflow at Mooring 32. There were two modes at 60 m at both moorings, but they were out-of-phase. Mode 1 was northward at Mooring 31 and southward at 32. These modes also reflect the estuarine inflow/outflow, as the level of no-net-motion rises from west to east (Figures 21-21), with outflow above and to the west.

Mode 2 at 60 m at these moorings was southward at Mooring 31 in mid channel and northward at Mooring 32 near Whidbey Shoal. Figure 74 shows that a major flow change from outflow to inflow occurred at Mooring 31 about 5/06/01, and it was as a complete reversal to inflow at the surface and outflow at depth. This reversal occurred during a week-long period of northerly winds (to the south). Figure 75 shows at Mooring 32 at the same time that the flow became southward at all depths, which is mode 1 at this location. Thus, wind event created the mode 2 flow at the middle mooring, but it caused a large augmentation of mode 1 at the eastern mooring. Mode 1 (or 2, etc.) does not have to occur simultaneously everywhere. It just indicates the most frequent flow occurrences.

Mode 2 at 100 and 140 m at Mooring 31 in mid channel was caused by the same wind event that reversed the inflow/outflow throughout the water column. Mode 2 at 60 m at Mooring 32 was northward flow. It appears to be caused at various times by weak or northerly (to the south) winds causing compensation flows and deepening of the level of no-net-motion that is near this depth (Figures 20-21).

5.5 Drogue Trajectory Length and Speed

Drogues provide estimates of current velocity at an array of locations as they drift in the Triple Junction. In order to compare drogues with currents observed at fixed locations with current meters, the total distance that a drogue traveled was determined for six drogues that traveled within the Triple Junction for six days (Table 11). Mean drogue speed was determined as the total elapsed distance divided by the total elapsed time.

In six days, the drogues traveled 65 to 109 km, equivalent to mean drogue speeds varying between 13 and 21 cm/s. These values lie intermediate to the mean speeds from current meters (0-10 cm/s), and flood/ebb tidal speeds (20-50 cm/s). These latter values are the speeds in the dominant ebb and flood direction. Substantial amounts of time, however, are spent not in these directions but swinging around the compass. A simple comparison can be made to the tidal current speeds by considering the distance drogues would travel if they moved back and forth with a simple sinusoidal tide. In this idealized case, the mean drogue speed would be approximately 0.64 times the maximum tidal speed. This suggests the drogues were moved by tidal speeds between 20 and 30 cm/s.

Most drogue trajectories did not display a simple back and forth tidal motion, but a combination of tidal motion and advection throughout the Triple Junction. A simple comparison can be made with the scale of the Triple Junction if the drogue motion is taken as purely advective. At the sea surface, the Triple Junction measures approximately 10 by 20 km. As the distances traveled by the drogues range between 60 and 110 km, they could have traveled the equivalent to three to six times the length or once or twice around the perimeter of Triple Junction, if not for their tidal motion.

Drogue G5, shown in Figure 52, is an interesting case study. It was released off Point Wells near the nominal depth of no-net-motion at 125 m. For six days, it traveled largely north and south with a range of approximately 6 km. Though it's mean speed was near zero as anticipated from the zero depth of no-net-motion, it traveled a total distance of 89 km, equivalent to 15 north and south cycles over its range, with a mean trajectory speed of 17.2 cm/s.

Table 11.
Drogue Trajectory Statistics

Drogue	Depth (m) / duration (days)	Length (km)	Speed (cm/s)
D5	25 m/ 6 days	68.1	13.1
K3	55 m/ 6 days	109	21.0
F5	125 m/ 6 days	74.0	14.3
F7	125 m/ 6 days	65.4	12.6
G7	125 m/ 6 days	67.3	13.0
G5	125 m/ 6 days	89.0	17.2

5.6 Drifter Escapement

This section considers the drogues and drift cards that exited Puget Sound north of Point No Point into the southern end of Admiralty Inlet (escaped). The highest escapement occurred near the sea surface. In the upper few meters 56% of drift cards and 69% of drogues escaped, and at 10 meters 71% of the drogues escaped (Ebbesmeyer et al., 2001). Differences between these three results are not considered significant due to the limited number of drogue releases. At approximately 25 m, escapement decreased to 27%, attributed partly to the influence of Whidbey Shoal and partly to decreasing estuarine outflow. Below the depth of the shoal, escapement decreased to 17%, but it is unclear whether this is a significant decrease from 27% above the shoal.

The percentage of drift cards that were recovered north of Point No Point can be found by combining the recoveries in Admiralty Inlet and the Strait of Juan de Fuca in Table 7. This is equivalent to the escapement percentage. The maximum escapement during deployments 1-9 occurred at release sites 1, 5, and 7, the offshore card sites at Possession Sound, Point Wells, and Pipers Creek, respectively. During deployments 10-14, the maximum occurred at the furthest offshore sites near Edwards Point and Point Wells, but release sites off Edmonds all showed high recoveries within Puget Sound.

Below the depth of Whidbey Shoal, drogues were considered to have exited Puget Sound if they drifted north of Point-No-Point or became grounded along the eastern side of the Whidbey Shoal. The fraction of drogues “escaping” increased at 110-120 m, but too few drogues were released for this result to be significant, with only eleven drogues grounding along the eastern flanks of Whidbey Shoal.

This is the region of tidal convergence discussed in Section 5.3. Flow may either go around the shoal or possibly upwell onto the shoal, depending on the depth and flow speed (MacCready et al., 2001). The convergence may provide a process for water, and thus drifters, at intermediate depths to escape into Admiralty Inlet.

5.7 Volume Transport

The mean transport of water has been estimated over the years to characterize the estuarine transport in various segments of the Main Basin. Some of these estimates are given in Table 12. Table 13 provides estimates of the mean estuarine flow through the two flow layers off Edwards and Point Wells using the observations from this study. The four estimates in Table 13 average 27,069 m³/s. Prior to this study, the highest volume transport in Puget Sound equaled approximately 27,000 m³/s in Colvos and East passages (Table 12).

Theoretically, the outflowing volume transport should exceed the inflowing value by the river discharge landward of the section. Since the present estimates differ by several thousand cubic meters per second and exceed the upstream river discharge (~500 m³/s), the differences are attributable to errors in estimating the transports arising from uncertainties in the flows unresolved near the channel walls and the sea surface. Despite the errors, the transports in the upper and lower layers differ by less than 5-10%, errors consistent with those of previous studies.

Table 12.
Historic Estimates Of Volume Transports

Location	Volume Transport (m ³ /s)	Reference
Colvos Passage	27,000	Ebbesmeyer et al. (1984)
East Passage	23,000 (landward)	Bretschneider et al. (1985)
Meadow Point	16,000	Cokelet et al. (1990)
Point Wells	28,320	This study
Edwards Point	25,818	This study
Admiralty Inlet	17,000	Average of Ebbesmeyer et al. (1984)

Table 13. Volume Transports in The North and South Flowing Estuarine Layers Off Point Wells and Edwards Point

Flow layer/ Location	Point Wells section (m ³ /s) February 20 –March 20, 2001	Edwards Point section (m ³ /s) July 14 –August 10, 2000
North flowing layer	26,880	25,354
South flowing layer	29,760	26,282
Average	28,320	25,818

Flow Perspective

This section provides a perspective on the volume transport through the Triple Junction region in relationship to some other flow rates, including local river and wastewater treatment plant flows. Flow rates have been converted into common metric units for comparison.

The following six flows were selected for comparison:

1. Wastewater Treatment Plant effluent: 100 million gallons per day (mgd) is representative of discharges from the largest facilities in the Puget Sound drainage basin. The average wet weather flow (wintertime) of the Brightwater treatment plant is projected to be 54 mgd at final capacity.
2. Duwamish River: the annual average discharge, chosen to represent a medium-sized river discharging into Puget Sound.
3. Total Puget Sound river discharge: the sum of the annual average discharge of all rivers emptying into Puget Sound.
4. Saratoga Passage: volume transport flowing north to Deception Pass from the Triple Junction.
5. Point Wells and Edwards Point: two transects (this study) where current meters placed across channel with the least separation between meters.

6. Colvos Passage: the largest volume transport known in Puget Sound prior to this study.
7. Tidal flux: during the average flood or ebb tide lasting approximately six hours, this is the volume transport of water flowing through the Point Wells and Edwards Point transects. The volume transport associated with the tides was estimated as follows using volumetric data for Puget Sound previously computed by McLellan (1954). Specifically, the volume between mean high water and mean low water inland of Point Wells was divided by six hours, the average time elapsed between the high and low waters.

Table 14.
Types of Water Flow and Associated Units

Flow Type	Conventional Flow Units	Metric Flow Units (m³/s)	Approximate non-dimensional Units (WWTP as basis)
Wastewater Treatment Plant (WWTP) effluent discharge	100 mgd	4	1
Duwamish River annual average discharge	900 ft ³ /s	25	6
Total annual average Puget Sound river discharge	42,000 ft ³ /s	1,200	300
Saratoga Passage volume transport	2,000 m ³ /s	2,000	500
Point Wells & Edwards Point volume transport	27,000 m ³ /s	27,000	7,000
Colvos Passage volume transport	27,000 m ³ /s	27,000	7,000
Point Wells tidal flux	270,000 m ³ /s	270,000	70,000

Overall, the flows vary over five orders of magnitude (Table 14), from the effluent discharged into Puget Sound from the treatment plant discharge (4 m³/s) to the ebb and flood tidal flux through the Triple Junction (270,000 m³/s). The various flows were then converted to a dimensionless scale by dividing them by the smallest flow, the discharge from the large wastewater treatment plant. The various flows range over five orders of magnitude up to 70,000 times the treatment plant discharge (4 m³/s).

5.8 Secondary Flow

Both the tidal and mean flow is primarily orientated in the land-ward or sea-ward directions. Secondary flows involve eddies, cross-channel flow, and recirculation patterns that do not contribute to the primary water motion. The cross-channel variation in mean currents observed between Point Wells and Edwards Point suggests a possible recirculation in this portion of the Triple Junction. Along the western side of the basin, the mean flow is southward at nearly all depths, while on the eastern side, the mean flow is northward from the surface to a depth of 120 m. Within this same region, density does not have a significant east-west variation (King County, 2001), suggesting vertical motion is small. In this case, it is plausible that a water mass may travel northward along the eastern side, then return south along the western side.

Direct observational evidence of this recirculation is mixed, with some drifters following this pattern, but many others following trajectories that do not. One drogue (#5) released during deployment F with a sail depth of 120-130 meters is perhaps the best example of this pattern (Figure 48). Released north of Edmonds, this drogue completed one and a half circuits roughly between Point Jefferson and Edmonds. Whereas drogues released during Dye Study 1 from Browns Bay moved westward and then south along the Kitsap Peninsula, but subsequently moved north and into Admiralty Inlet along west side of the Triple Junction. The composite trajectories of all drogues released off Point Wells, shown in Figures 50-52 for three depth ranges, 0-25m, 55-75m, and 105-155m respectfully, show little tendency for drogues to move westward and return southward.

Drift cards only provide release and recovery locations, without any information of their trajectory. As discussed in Section 4.1, Point Jefferson was a collection location for drift cards released along the eastern shoreline to wash ashore. Based on the current meter and drogue observations, it is assumed that these cards likely traveled westward across the Triple Junction, then southward along the Kitsap Peninsula before washing ashore at Point Jefferson. The recovery of cards from the same release sites was often substantially lower at the Meadow Point and Point Wells collection regions, suggesting that if the cards were moving southward along the Kitsap Peninsula, they often did not move back to the eastern shoreline.

5.9 Onshore Currents

The effects of cross-channel currents oriented perpendicular to the shore (i.e., onshore currents) are particularly important near the shore. A common analysis technique used to examine current meter data is the construction of progressive vector diagrams. These diagrams provide a simple analysis of where water parcels would travel in the vicinity of the observations under the assumption that the currents are spatially homogeneous. The resulting trajectories can then be used to determine a rough estimate of how far water parcels would move within a given time period. Often this analysis is used to provide an indication of onshore currents by computing the fraction of water parcels that are displaced beyond the shoreline.

A progressive vector diagram is constructed by plotting the observed current vectors in sequence and is intended to provide a visual appreciation of the movement of water particles. Let $\mathbf{u}(t)$ ($0 < t < T$) be the measured current velocity vector. Then at time T the location of tracer particles released at time $t < T$ is now at

$$\mathbf{x}(\tau, T) = \int_{\tau}^T \mathbf{u}(t) dt,$$

where $\mathbf{x} = 0$ is the release location.

For each combination of T and t , the value $\mathbf{x}(t, T)$ can be tested for whether or not it is shoreward of some imaginary line (such as the shoreline). Varying t and T provides some measure of the probability of transport to the shore within various times.

This type of analysis is limited by the assumption that the currents are spatially uniform around the current meter location. While this may be reasonable for fairly large distances in oceanic locations, the current ellipses derived from these observations show that the

direction and magnitude of the currents possess significant spatial variations within the Triple Junction region. As a result, this analysis will be increasingly inaccurate as the distance from the observation location increases.

The velocity vector $u(t)$ was formed by vertically averaging the raw current meter data over a 20-m interval. Then the displacement, $x(t,T)$, was computed for the entire time series at each current meter location. The fraction of the calculated displacements that crossed the shoreline was computed for each increment in time ($T-t$). It must be pointed out again that this method of analysis is subject to the rather gross assumption that the current is spatially homogeneous and hence the results should be regarded only as a guide and as a relative comparison between sites.

Figure 76 shows the percentage of progressive vectors reaching the shore for time intervals up to 24 hours in the depth range of 20-40 m at moorings 5, 12, 14, 18, and 24 closest to the eastern shore between Point Wells and into Possession Sound (see Figure 2). Each curve generally rises with time reaching their maximum percentages after 24 hours. The highest percentage (80%) occurs at Mooring 12 located off the southern end of Browns Bay. To the north and south of Mooring 12, the percentages decrease to the range of 45% off Picnic Point (Mooring 18) and 49% off Edwards Point (Mooring 5), and to the range of 25% off Point Wells (Mooring 24) and 30% in Possession Sound (Mooring 14).

It must be emphasized that these moorings were deployed during differing tidal and wind conditions so the percentages cannot be considered synoptic.

Drift cards are recovered after they wash up along the shore, and thus reflect onshore currents. Cards found within the concentration zones described in Section 4.1 appear to reflect physical mechanisms of water movement. These are described below in order of the number cards reported along these shores.

Edwards Point. These appear to result from onshore currents that occur twice daily during flood tides. This current pattern is supported by tidal ellipses computed from ADCP current meters and patterns in the University of Washington tidal hydraulic model (see Section 5.3).

Point Jefferson. The cards found at Point Jefferson and vicinity originated from along the eastern shore from Point Wells and northward. To reach Point Jefferson, these cards traveled westward across the Triple Junction, then southward in the Kitsap counter current.

Meadow Point. Most of the cards found in this zone appear to have traveled south along the shore from the vicinity of Point Wells.

Point Wells and Picnic Point. The relatively few cards found in these regions suggest little onshore movement.

5.9.1 Estimated Effluent Concentration at Shoreline Stations

The shoreline concentration data allow assessment of the long-term accumulation of effluent for a simulated discharge. The methods of Hubbard and Stamper (1972) have been used to assess long-term accumulation of effluent at the shoreline stations for a 54 mgd ($2.4 \text{ m}^3/\text{s}$) discharge. This method uses the principal of superposition to establish a quasi-steady effluent concentration for each monitoring site. Since the duration of each dye injection was one semi-diurnal tide cycle (approximately 12.4 hours), the peak measured

concentrations of each successive semi-diurnal period are added. The sum of these peaks is the quasi-steady peak effluent concentration for the shoreline stations.

The modeling for a 54 mgd discharge is conducted two ways. The first model provides conservative (*i.e.* worst-case) estimates of effluent concentration because it does not account for the rapid initial mixing that occurs to a buoyant plume. The second method adjusts each measured shoreline concentration by the time-weighted difference in farfield mixing due to initial plume dimensions. The second method is intended to be a more realistic prediction of shoreline concentrations than the first method.

The predictions of both modeling methods must be considered first-order estimates, or order-of-magnitude estimates. Precision calculations are not possible due to the low dye concentrations measured compared to background, and the broad modeling assumptions in the second modeling method.

The predicted effluent dilution factors using method 1 range from a minimum of approximately 700:1 for the Browns Bay discharge site to over 22,000:1 for all stations with the Edwards Point deep discharge site. Under method 2, the minimum dilution factors were approximately 7,000:1 for the Browns Bay site, and exceeded 200,000:1 for Edwards Point.

5.9.2 Dye Studies Summary

The shoreline effluent concentration cannot be estimated from the first two dye release studies because of the winds that occurred on Day 2 of both. The weather conditions forced cessation of the beach sampling during critical periods of the study. The higher turbidity also affected the measurement of beach samples when the study resumed. No conjecture is offered of the impact the winds may have had on transporting dye out of the study area, or what would have prevailed had the winds not occurred.

All of the studies except the fifth conclusively detected dye at shoreline stations. None of the measured shoreline concentrations exceeded an order of magnitude above background. The highest concentrations occurred during the Browns Bay injections (studies 1 and 3), by a factor of approximately two over the Point Wells site. There was no indication of any shoreline contact of dye injected at the Edwards Point deep station (study 5).

5.10 Horizontal Dispersion Estimates

During releases I, J, K, multiple drogues were clustered around a single initial location. The increasing separation of the drogues within each release was used to determine horizontal dispersion versus time. To quantify the drogue dispersion, a bivariate normal distribution was used to fit ellipses around the drogue positions at half-hour intervals. From this distribution, the standard deviations of drogue positions along the principle axes were obtained and the mean square displacement from the centroid. Figure 77 shows the expanding size of the drogue clusters with time.

Focusing on the cluster in Release J, the drogues moved as a relatively tight group for the first day and a half until they reached Whidbey Shoal and bumped into the bottom (Figure

78). The cluster size appears to grow and contract with the tidal motion, but to obtain a conservative estimate for the dispersion coefficient, the rate of grow was estimated for the minimum cluster size (Figure 79, dashed line). This growth rate corresponds to a dispersion coefficient of $2,800 \text{ cm}^2/\text{s}$. The dispersion coefficients for the other two drogue releases are more than an order of magnitude larger than this value (Figure 80), indicating that a high degree of mixing is common in the Triple Junction.

5.11 Seasonal Variability

Yearlong Aanderaa current meter moorings were maintained at reference sites in the Main Basin, Possession Sound and Admiralty Inlet (Figure 2) from July 2000 to July 2001. The time series of currents, temperature, salinity, and density are included in Appendix L. Temporal variations of salinity and temperature (hence density) in the Main Basin and Possession Sound generally reflect those of the inflowing water from Admiralty Inlet. Figures 81 and 82 show the yearlong time series of temperature and salinity in the Main Basin.

Puget Sound is affected by seasonal changes in climate, wind patterns and river runoff. The combined influences of ambient atmospheric temperature, solar radiation, and the temperature of water flowing in from the Strait of Juan de Fuca are the major influences on the temperature within Puget Sound. Temperature cycles from a maximum in late summer to a minimum in winter. Summer heating results in a top to bottom temperature range of approximately one degree, and winter cooling results in near-isothermal conditions by late winter (Figure 81).

Historical data show that water mass properties in Puget Sound follow a general seasonal cycle. A composite plot of temperature at 100 m off Point Jefferson (Figure 83) shows warmest values in late August to early September, and coldest values in February through March. A seven component Fourier fit shows a seasonal cycle with peak-to-valley range of 4.4°C , about a third of the range in the diurnal average air temperature over Puget Sound. Salinity has a well-established seasonal cycle (Figure 84), with highest values seen in October and lowest values in spring months with a yearly range of about 1.1 psu. The salinity data has considerably more scatter about the fitted curve than temperature, with the minimum value having nearly as much range as the seasonal cycle itself. Further, when different years are broken out (Figure 85), 1997 stands out as having an anomalously low fall maximum.

The inflowing water from the Strait of Juan de Fuca originates offshore of Washington and Vancouver Island in the Pacific Ocean. Northerly winds (to the south) along the Washington coast, in concert with the effect of the earth's rotation, cause surface waters in this region to move offshore, and deeper, colder, and more saline waters, to upwell into the Strait and Puget Sound. Alternatively, coastal winds blowing from the south drive surface waters toward the shore, pushing fresher and warmer waters downwards. During a typical year, downwelling occurs during fall and winter (October-March) and upwelling during spring and summer (April-September). NOAA computes an upwelling index representing the strength of coastal upwelling/downwelling from predictions of the offshore pressure (wind) field.

The upwelling index is shown in Figure 86 for a three year period extending from one year before to one year after this study, along with the long term daily mean of the upwelling

index. In general, the Upwelling Index appears to cycle normally during these three years. As mentioned during the discussion of bottom water intrusions (Section 5.3), the salinity of these intrusions appears to peak in late summer or fall. This timing is consistent with the summer upwelling of saltier water into the Strait of Juan de Fuca and a couple month transit time to Admiralty Inlet.

Observations off Edwards Point during Deployment 8 (Nov 30, 2001 – Jan. 7, 2002) showed a shift in the vertical structure of the currents. Whereas the currents observed in Deployment 1 had a profile typical of two-layer flow, with the maximum inflow at depth, Deployment 8 appeared to be characteristic of a three-layer flow, with an inflow at mid-depth. Figure 87 shows 28-day average currents at three moorings off Edwards Point. Moorings 3 and 50 are approximately a mile apart but Mooring 50 was deployed 16 months after Mooring 3. Mooring 51 is also shown and provided added confidence in the vertical structure seen at Mooring 50. Note that Mooring 50 was obtained with Aanderaa current meters and Mooring 51 with an ADCP meter. It is unclear when this shift might have occurred. The previous deployment ended July 25, 2001, and during this period in 2000, moorings were located further north in Browns Bay and Possession Sound.

Figure 88 shows the histograms of Lanczos filtered currents at Moorings 3 and 50. The histograms obtained in different years are quite different and confirm the substantial change in the vertical structure of the horizontal currents. For reasons of flow continuity, we hypothesize that these structural changes also occurred off Point Wells.

Comparing the currents with winds, upwelling and river discharge do not lead to clear conclusions as to cause and effect. Unfortunately, the cause of this variation of current structure is unclear. Potentially, this could be a result of a seasonal flow change due to less dense waters entering through Admiralty Inlet. Alternatively, the resumption of normal rainfall and river flows in the winter of 2001, and a stronger estuarine flow from Possession Sound could have shifted the three-layer type flow pattern observed in Possession Sound further south. Or, possibly, this could indicate a interannual shift in the circulation pattern.

Most rivers emptying into Puget Sound show a distinct seasonal cycle, with increased flows during the wet winter months and spring snow melt. The region received below normal precipitation from approximately November 2000 to September 2001, the second most severe dry period since the winter of 1976 through 1977, resulting in notable departures from the long-term average runoff (Figure 89). This suggests that the estuarine circulation would normally be stronger than observed during this study, but the lack of comparable data makes it difficult to estimate the effect of the anomalously dry winter on Puget Sound's circulation.

The reduced exchange rate of estuarine circulation is collaborated by a simple dynamical model of Puget Sound. The model, designed at the University of Washington to explore seasonal and lower-frequency variability, predicted that the exchange flow between the Main Basin and Admiralty Inlet during the period of observations was about 20% below the previous ten year average (A. Babson, personal communication).

Figure 90 shows yearlong time series of along-channel currents at six depths at the Main Basin Aanderaa current meter site. Also shown are polynomial fits to the shallowest and deepest records (24; 177 m). The difference in current speed (shear) over this depth range decreases substantially as the year progresses. To examine shear more closely, Figure 91 shows the yearlong time series of the current difference between 24 and 147 m. During summer 2000, before the dry winter, the magnitude of the current difference was

approximately 25 cm/s, but by the next summer the difference had decreased by half to approximately 12 cm/s.

This temporal variation of current differences was analyzed in more detail by examining the current shear above and below the depth of no net motion, which separates the inflowing and outflowing layers. Table 15 lists the north-south components of the mean velocity, the depth of no net motion (Z_0) and the current shear above (S_u) and below (S_l) the depth Z_0 . Z_0 averages 80 m with a standard deviation of 6.2 m. The associated coefficient of variation indicates that Z_0 varies by only 7.8% of the mean value. The depth of no-net-motion, therefore, may be considered constant during the study period, a result found previously at a site farther to the south (Ebbesmeyer et al, 1989). Shear was computed in the upper and lower layers as the difference in the north-south currents between 24 and 57 m and 112 and 177 m, respectively. Shear in the upper layer averages 25% greater than in the lower layer. Shear in the layers are correlated ($r = -0.74$), and the coefficients of variation are nearly identical (34% vs. 39%, respectively).

Table 15.
Currents at the Main Basin Reference Site

Depth (m)/ Deployment # (28 day interval)	1a	2a	2b	3a	3b	3c	4a	4b	5a	5b	6a	7a	Mean	Standard Deviation	Coefficient of Variation
24	11.1	14.4	7.6	11.3	8.8	3.7	7.3	8.9	7.5	7.8	6.7	8.4	8.6	2.69	0.31
57	5.5	7.1	5.4	6.4	4.7	2.1	4.3	3.9	4.3	3.1	2.6	2.9	4.4	1.55	0.35
87	-0.41	-0.41	-0.8	ND	ND	ND	-0.14	-2.6	1.5	0	-2	-2.4	-0.8	1.32	-1.63
112	-7	-8.6	-7.1	-7.7	-7.7	-5.7	-5	-8	-5.5	-4.6	-3.7	-4.9	-6.3	1.58	-0.25
147	-10.9	-14.8	-12.5	-13.3	-12.6	-8.1	-10.2	-12.5	-9.3	-6.7	-5.2	-6.7	-10.2	3.05	-0.30
177	-13.7	-18.2	-12.4	-16.7	-15.6	-10.1	-13.6	-16.6	ND	ND	-6.2	-7.5	-13.1	4.03	-0.31
No-net motion depth (m)	85	85	83	82	78	72	86	75	92	87	74	73	81.1	6.52	0.08
Upper Layer (24-57m) shear (10^{-3} sec^{-1})	-0.17	-0.22	-0.067	-0.15	-0.12	-0.048	-0.091	-0.15	-0.10	-0.14	-0.12	-0.17	-0.129	0.0482	-0.37
Lower Layer (112-177m) shear (10^{-3} sec^{-1})	-0.10	-0.15	-0.082	-0.14	-0.12	-0.068	-0.13	-0.13	-0.11	-0.060	-0.038	-0.040	-0.0976	0.0390	-0.40

Notes:

North-south 28-day mean currents at the Reference Mooring and associated depth of no-net motion (Z_0), and shear in the upper and lower layers.

Meter depths are nominal values.

a, b, c, are successive 28-day means (see Table 5);

ND = no data

Coefficient of variation = standard deviation divided by the mean value.

5.12 Long-term Variability

Puget Sound is a fjord estuary, and its circulation, despite the complexity, is essentially a two-layer exchange system driven by the density contrast between fresh and oceanic waters and regulated by tidal mixing at sills (Ebbesmeyer and Barnes, 1980). Circulatory conditions in Puget Sound would thus be influenced by factors controlling these elements. Of these, tidal mixing is astronomical in its origin, and can be considered stable over time scales longer than a year. Thus, the major factors affecting Puget Sound circulation over long time scales are those that influence the river input and oceanic conditions outside the mouth of Puget Sound (in the Strait of Juan de Fuca and eventually in the northeastern Pacific). Both would naturally feel the effect of local and global climate. Thus, Puget Sound's circulation would be expected to respond to climate change (Ebbesmeyer et al., 1989).

Puget Sound appears to be sensitive to variability in physical factors influencing its circulation. Nevertheless, the Main Basin remains a well-ventilated basin due to the vigorous mixing at the sills in Admiralty Inlet and The Narrows. This appears to be a defining characteristic of Puget Sound, which gives it a robust circulation.

Understanding Puget Sound's sensitivity to such changes requires long-term data. A program of regular hydrographic measurements at monthly intervals in Puget Sound by the University of Washington was in place from 1932 through 1941, when the Second World War halted the program. Regular measurements did not resume until 1951. After 1956, they became increasingly sporadic and ceased after 1975. As a result we have a data set whose strength is the long duration, but which poses challenges in terms of irregular sampling (see Collias, 1970).

The UW's cessation of regular measurements has been largely taken up by state and local governments. The Washington State Department of Ecology (WDOE) has conducted float-plane based oceanographic measurements since 1973 in Puget Sound and other inland state waters. Until recently, measurements were done discretely near the surface, (5, 10, 30 m). Recently WDOE acquired a CTD package enabling full-depth measurements from a float plane.

King County Department of Natural Resources has monitored the marine environment under its jurisdiction. Notable is a water quality time series at a location off Point Jefferson (KSBP01; Figure 2) that has continued since 1990 at roughly a monthly interval. Comparison of this data set from data obtained from the UW's recent PRISM surveys of Puget Sound shows that data from this location is representative of much of the Main Basin (M. Kawase, personal communication) This discussion will focus on results from this time series.

Since the data set consists of instantaneous measurements at monthly or longer intervals, aliasing of high-frequency variability (such as tides, winds and intraseasonal intrusions) presents serious complications. Puget Sound's upper layers are particularly sensitive to such variability; hence the focus on the deep water variability in this discussion. In order to assess the significance of year-to-year variability, we need at least an estimate of the amplitude of the aliased signal. For the Point Jefferson time series, NOAA data from 1975 through 1976 (Cannon and Laird, 1978) from a nearby current meter mooring were used for estimating amplitudes of tidal and intraseasonal variability.

Intraseasonal variability is pronounced at 200 m (presumably reflecting bottom water intrusions) but relatively absent at 100 m, hence the latter depth level is chosen for this discussion. Amplitude of tidal variability is relatively small, of the order of 0.26°C for temperature and 0.11 PSU for salinity (estimated as twice the variance of the high-pass filtered time series). When the departure from the fitted seasonal cycle (Section 5.11) is plotted with this uncertainty bound (Figure 92; only salinity is shown), it is apparent that the time series contains interannual variability that cannot be accounted for by aliasing of tidal variability. In particular, the fresh anomaly of the late-1997 (as well as that of the previous winter of 1996) is significant.

Barnes and Collias (1958) explain that the salinity peak in the fall signals the arrival of water upwelled along the Washington coast during the previous summer. During a normal year, this intrusion changes the character of the exchange circulation temporarily, with the upwelled coastal water occupying the deep basins and causing the water from the sills to enter at mid-depths rather than at the bottom, until the former is eroded away due to mixing. As it turns out, in 1997 anomalous wind conditions along the Pacific Coast of northern California to Washington resulted in a shutdown of summertime upwelling which appears reflected in the Puget Sound data. This anomaly appears to be part of the global atmospheric disruption due to the 1997 El Nino event. This indicates the significant influence the coastal conditions can have upon the hydrography and circulation of Puget Sound, as expected from the estuarine character of its circulation. On the other hand, the great variability in the spring minimum in salinity does not have a simple explanation. A comparison of the salinity anomaly with river flow data from the same period did not reveal a strong correlation.

Similar anomaly analyses were applied to the historical data collected at the Point Jefferson location from 1951 to 1975. The seasonal cycle is stable even over this time scale, and the anomaly time series for temperature and salinity reveal significant variabilities at interannual and longer time scales (Figures 93, 94). Of particular interest is what appears to be a four- to five-year periodicity in salinity anomaly. Unfortunately, data gaps at crucial periods makes it difficult to assess influence of factors such as El Nino-Southern Oscillation.

Historical data from stations in Main Basin show that the wintertime salinity of the deep layer of Puget Sound has a large year-to-year variability with a peak-to-valley range of 1.2 PSU, which is comparable to the range of seasonal variability itself. River discharge appears to be the primary factor controlling the wintertime salinity. Average salinity anomaly for the winter months shows substantial correlation ($r^2 = 0.36$) with the Skagit River discharge over the same months (M. Kawase, personal communication).

The mean currents listed in Table 12 indicate that the highest inflow speeds occurred near the sea floor. This type of profile is indicative of the warm, dry climate regime previously described in detail by Ebbesmeyer et al. (1989). During this dry regime, oceanic and local environment factors favor maximum inflow near the seafloor as opposed to mid depths during the opposite cold, wet regimes. The warm, dry regime has persisted since 1977.

5.13 Flow Schematics

It is often useful to create simplified pictures, or schematics, of the overall circulation. These schematics describe the general pattern of circulation and how this pattern tended to

vary under different conditions. The circulation within Puget Sound and the Triple Junction region is complex, and the limited sampling window of this study cannot adequately detail longer term variability, so these pictures are limited to providing a general view of the circulation. To this extent, the observations from the current meters at fixed locations and from drifters (drift cards, drogues, dye) were combined to create schematics of the mean flow and the associated variability.

Figures 95 and 96 are schematic presentations of the dominant mean flow patterns in the outflowing layer near the sea surface and in the mid depth inflowing layer in the Triple Junction. The shallower map is above the depths of the Whidbey and Jefferson shoals and represents the near-surface flow, some of which might be seen in the hydraulic tidal model. The deeper map is below the depth of the shoals. In the Main Basin this layer primarily is inflowing bottom water, but in some locations it also includes outflowing water or a transition between inflowing and outflowing. In Possession Sound this layer is the dominant inflow level.

Near Surface Mean Flow

Figure 95 shows the schematic mean flow representative of the upper 40 to 50 m that results from estuarine circulation and some tidal effects. The major features are:

- 1) Northward mean flow out of the Main Basin occurs from Point Jefferson through the Triple Junction and into Admiralty Inlet. This is the estuarine surface outflow due to river inflow, and is a dominant feature in the maps of mean currents.
- 2) Southward mean flow out of Possession Sound converges with the Main Basin outflow over the Whidbey Shoal. This flow is a relatively shallow estuarine surface outflow that is concentrated on the Whidbey Island side of Possession Sound. The convergence with the Main Basin outflow is evident from drogue trajectories and is suggested in current meter observations.
- 3) Southward nearshore flow along the Kitsap Peninsula is particularly evident from drift card recoveries and drogue trajectories, and partly from current meter records. This southward flow forms one component of a counter-clockwise recirculation in the Main Basin between Jefferson and Whidbey shoals that was apparent in several drifter observations.
- 4) Converging and diverging flows occur in the region off Browns Bay. They are partly a result of convergence of Main Basin and Possession Sound outflows, noted above, but primarily are the net effects from ebb and flood tidal currents, respectively. They are major features in hydraulic model observations. The divergence includes onshore flow, and accounts both for the large number of drift cards recovered in this region and for the beaching of numerous drogues.

Mid Depth Mean Flow

Figure 96 shows the mean flow at about 100 m that represents mid depth estuarine circulation and some tidal effects. The major features are:

- 1) Southward flow from Admiralty Inlet diverges south of Whidbey Shoal with part flowing into the Main Basin and part into Possession Sound. This water is part of the inflowing estuarine circulation caused by the higher salinity water outside of Admiralty

Inlet. The southward component in the Main Basin is continuous with inflowing bottom water.

- 2) Northward flow into Possession Sound, unlike the Main Basin, is maximum at mid depths. There are variations about the mean, including occasional reversals, but the long-term mean is northward. Although this pattern is evident in the current meter observations, no drogues at this level drifted beyond the entrance to Possession Sound. Those that drifted that far, reversed direction, and flowed southward into the convergence zone that, at this level, was between Browns Bay and Edwards Point.
- 3) Northward flow occurs along the east side of the Main Basin in the region north and south of Point Wells. It converges with the Admiralty inflow and flows toward Possession Sound. This is the only known deep northward flow in the Main Basin, and it possibly is caused by curvature of Puget Sound as water flows around Point Jefferson Shoal to the South..
- 4) Convergence and divergence of flows occur in the region north of Edwards Point. This region has shifted southwestward from that for the surface flow because the incoming and outgoing tides are constrained to flow west of Whidbey Shoal. This convergence is shown by the large number of drogues that flow to the southern part of Whidbey Shoal and either ground, flow over, or are dragged around the west end of the shoal. The canyon at the west end of the shoal apparently plays a major role in flow going over or around the shoal. If speeds are sufficiently large, the flow can go up canyon and over the shoal. If not, it goes around the shoal. Similar effects have been observed elsewhere in Puget Sound (MacCready et al., 2001) and in flow around a coastal headland (Geyer and Signell, 1990).

Deep flow (not shown here; see map of 140 m flow, Figure 13) is southward everywhere in the Main Basin. The inflow from Admiralty Inlet occurs west of Whidbey Shoal. South of the shoal part of the flow diverges and flows northward into Possession Sound. The divergence is centered approximately on Edwards Point as shown for the mid-depth flow.

Figures 97 and 98 are schematics of the flow variability near the surface and at mid depths. These figures correspond to the two figures of mean flow (Figures 95-96). The variability shown by the drogues and current meters was caused mostly by wind changes with durations lasting from a day to a week, and the magnitudes of the variations were comparable to the mean currents. As an example, one drogue drifted across most of the Triple Junction in patterns completely different from any pattern suggested by the mean flow.

Near Surface Flow Variability

Figure 97 shows patterns of flow variations near the surface and are representative down to 40 to 50 m. The major features are:

- 1) Winds from the south increase the outflow in the Main Basin, but decrease and sometime reverse the outflow from Possession Sound. Winds from the north, however, cause an opposite effect, and increase the outflow from Possession Sound, but decrease and sometimes reverse the outflow from the Main Basin.
- 2) Cross-channel flow occurs in the Triple Junction from northeast of Edwards Point to the Kitsap Peninsula may be caused by winds from the south (see Section 5.4). Drogue

trajectories and drift card recoveries showed these flow patterns. Alternatively, winds from the north tended to cause flow to the northeast from Edwards Point (observed in current meter records). There also appeared to be a cross-channel flow evident in the streak photos from the physical model of Puget Sound.

- 3) Northward near shore flows from Richmond Beach toward and into Possession Sound were observed at times from drogue trajectories.

Mid Depth Flow Variability

Figure 98 shows patterns of flow variations at mid depths near 100 m. The major features are:

- 1) Winds from the south augment the surface outflow in the Main Basin, and cause an increased compensating inflow at mid-depths. In Possession Sound, the effect is opposite causing decreased inflow at mid-depths. Similarly, winds from the north decrease the mid-depth compensating flow in the Main Basin, and increase the mid-depth flow into Possession Sound.
- 2) Cross-channel flow at 100 m was similar to the flow at 20 m, southwestward from Browns Bay to Apple Cove Point. This pattern also seemed to be caused by winds from the south. Deep drogues flowed across channel, then southward along the Kitsap Peninsula, turned northward off Point Jefferson, and returned to the vicinity of Edwards Point. One drogue made this circuit twice. Winds from the north, however, tended to cause northeastward flow from Edwards Point at 100 m, similar to flow at 20 m (observed in current meter records and drogue trajectories).
- 3) Bottom-water intrusions into the Main Basin approximately occur at two week intervals and cause compensating northward flows at mid-depths (green arrows).
- 4) Flow convergence in the region between Edwards Point and Browns Bay was observed with deep drogues. They flowed toward, and then grounded on the east side of the Whidbey Shoal. Although the drogues grounded, the water should either flow north or south along the topography or be hydraulically raised onto the shoal, or some of both. The fate of this water cannot be determined from the present observations.

Onshore components of currents from Meadow Point to Possession Sound varied substantially as shown by drift card recoveries and by onshore currents computed from the current meter observations. The greatest drift card recoveries occurred from deployment sites offshore of the region between Edwards Point and Picnic Point. The associated onshore currents appeared to coincide with onshore directed flood currents as observed in the University of Washington hydraulic tidal model, on the tidal current mode maps, and by the tidal current ellipses computed from mooring observations.

6.0 SUMMARY

This study of the Triple Junction attempted to detail the physical oceanography of Puget Sound during the period July 2000 through January 2002. Observations included measuring currents with 56 moorings at fixed locations, tracking the release and recovery locations of 2702 drift cards, tracking 106 drogues at various depths, and conducting 5 dye releases.

Tidal currents accounted for most of the current variability. The tides are dominated by the semi-diurnal (twice a day) component. At Edmonds, the mean spring tidal range is 3.33 m (10.9 ft). The tidal currents flow in and out of Admiralty Inlet, diverging to, and converging from, the Main Basin and Possession Sound offshore of Edmonds. The relatively complex and irregular topography in this region creates horizontal gradients in the tidal flow, as the water flows around shoals and headlands and through narrow, constricted passages. This was reflected in the acute angles observed between ebb and flood current directions that occurred in many of the current meter records. Within the Triple Junction, a stronger flood current flows along the western shore between Kingston and Point-No-Point, and stronger ebb currents between Richmond Beach and Edmonds. Since the tidal excursion is approximately the distance between the Point Jefferson and Whidbey shoals, this appears to create a counterclockwise rotation in this part of the Main Basin. Typical tidal current speeds offshore of Edmonds are 0.3 m/s (0.6 kn).

Tidal currents in the Triple Junction are greatly influenced by the presence of the Whidbey Shoal that extends south from Whidbey Island at a depth of about 20 to 40 m. Flood currents above a depth of approximately 30 m flow from Admiralty Inlet over the Whidbey Shoal and diverge along the eastern shoreline offshore of Browns Bay. North of this divergence, flow is into Possession Sound, and south, into the Main Basin. At greater depths, the flood current is constrained west of Whidbey Shoal, and the divergence line shifts south to the vicinity of Edwards Point. Ebb currents converge in approximately the same locations as the flood currents diverge. Similar effects occur off the Point Jefferson Shoal.

Puget Sound has an estuarine flow, in addition to the tidal currents, with inflow of more dense saline water at depth and outflow of brackish water at the surface. Brackish (less saline) surface water is formed as fresh water from rivers mixes with the saline ocean water. The three largest rivers, the Skagit, Snohomish, and Stillaguamish, all empty into Whidbey Basin, creating a strong surface outflow from Possession Sound. The rivers in South Puget Sound and the Main Basin also create a brackish, outflowing surface layer that is less intense, but deeper, than the outflow from Possession Sound.

The current meter records were analyzed to separate the low-frequency, or non-tidal flow (i.e., estuarine and wind induced flow) from tidal motions. Because the tidal currents often were not 180° out-of-phase, the mean currents in these cases bisected the angles between ebb and flood directions. To solve this dilemma, low frequency modal currents were calculated. The low-frequency currents showed preferred directionality, varied over periods of days to months to a year, and were markedly influenced by the shoals off Point Jefferson and Whidbey Island. Most locations had flow in one direction. But near shore and substantial topographic features, the flow had two or three preferred directions (called modes). This multi-mode behavior was concentrated in the areas of the tidal convergence

and divergence, i.e., along the eastern shore from Edwards Point to north of Browns Bay and along the southern edge of Whidbey Shoal.

The first current mode accounted for the largest percentage of the low-frequency currents and defined a general pattern of long-term mean or prevailing currents. This pattern varied substantially on horizontal scales of the Triple Junction itself down to localized effects. One localized effect is the tidal rectification off the submarine extension of Edwards Point. This submerged headland deflects flooding waters to the southwest and ebbing waters to the northwest, resulting in westward flow in Mode 1 that is perpendicular to the prevailing northward flow in the rest of this region. The deepest northward flowing layer yet documented in Puget Sound (120-140 m) was found off Point Wells and Edwards Point.

The mean volume transport was 27,000 m³/s, equal to the prior largest measured transport in East and Colvos passages.

Saline ocean water enters Puget Sound over the two sills in Admiralty Inlet and then flows southward along the Main Basin and northward through Possession Sound into Whidbey Basin. Combined with the asymmetric tidal currents, this inflowing water creates a mean southward current along the western shore that extends from the bottom to near the surface. Along the eastern side of the Main Basin, the mean current is northward from the surface to 120 m, but southward below 120 m.

Modes 2 and 3 accounted for less of the low-frequency currents, and are correlated with wind and intrusion events. Winds create complex current patterns in the Triple Junction because they have opposing effects on the Main Basin and Possession Sound. A wind blowing from the north reinforces the surface water flowing south out of Possession Sound, and it opposes water flowing north out of the Main Basin. Similarly, a wind blowing from the south retards the southward surface outflow from Possession Sound while reinforcing the northward flowing water in the Main Basin. These opposing influences are reflected in the multiple flow modes observed in the general area from Edwards Point to north of Browns Bay. Mode 3 is sometimes caused by exceptionally strong wind events.

Winds also have pronounced effects on deeper currents. Winds blowing in the direction of the surface current increase both the surface current and a compensating flow in the opposite direction at about 100 m. Winds counter to the surface flow retard both the surface current and the compensating deep flow. The opposing nature of the wind forcing on Possession Sound and the Main Basin results in large, variable currents at depths around 100 m.

Intrusions of salty bottom water from the Strait of Juan de Fuca were observed a number of times during the year. The intrusions can penetrate the water column from the sea floor upwards to about 100 m during the strongest events. The majority of the water associated with an intrusion event flows southward along the deepest parts of the Main Basin, but there also is flow divergence off Edwards Point, and part of the intrusion propagates into Possession Sound. As with wind effects, there are compensating flows for intrusions. These flows appear as increased outflow at mid depths. Modes 2 and 3 in the deeper water are combinations of intrusion and wind events.

Surface currents were inferred by combining the shallowest current observations and reported locations of drift cards. Approximately 51% of the recovered cards (1,344) escaped from the Sound into Admiralty Inlet and beyond. Between Edwards Point and Browns Bay, flooding tides push surface waters onshore, and similar onshore ebbing

currents exist between Meadow Point and Boeing Creek. Three quarters of the drift cards recovered along the eastern shore from Paine Field south to the Ship Canal were recovered in these two areas of onshore currents. The second greatest drift card accumulation occurred in the vicinity of Point Jefferson. These appeared to have traveled westward across the Triple Junction, and then southward along the Kitsap Peninsula.

Drogue observations were used to integrate the individual current meter measurements together into qualitative circulation patterns within the Triple Junction. Drogue trajectories from multiple releases at the same location show that within a week the drogues may wind up almost anywhere in the Triple Junction. Drogue tracks reflect tidal currents and the three low-frequency modes, resulting in trajectories that often resemble neither the tides, prevailing flow, intrusions, or wind induced flow, but rather a complex blend of all four. One puzzling result was that no deep drogues (100+ m) were observed to enter Possession Sound, although mean currents indicated a persistent inflow at these depths.

Drogues released off Edwards Point and Point Wells gave the impression of a highly dispersive environment, and could be found throughout the Triple Junction within a week. The overall rate of dispersion was estimated from the spreading of clusters of drogues released together, and found to be similar to, and an order of magnitude larger than expected from diagrams of mixing in a wide variety of environments including lakes, estuaries and the coastal ocean (Okubo, 1971). Five separate tracer studies were conducted at three depths to examine the vertical, near-shore mixing. Each fluorescent dye release was tracked for up to five days by a vessel-towed array, and at shoreline stations from Picnic Point in the north to Carkeek Park in the south. The results showed rapid dilution and dispersal of dye from all release sites. The tracer release sites in Browns Bay, with release depths at 8 and 25 m, displayed the highest probabilities of shoreline contact, and at the highest concentration (*i.e.* lowest shoreline dilution factors). Comparable releases from the Point Wells area had fewer shoreline "hits" and at lower concentrations. The final release near Edwards Point, at a depth of 58 m, resulted in no contact with any of the shoreline monitoring stations.

This study has provided significant additional observations on the physical oceanography of Puget Sound focused on a region associated with the siting of a marine outfall for the Brightwater Treatment Plant. However, significant scientific questions beyond the needs of this project have arisen during the work. These are noted here because they could be of interest for future investigators: (1) What are the quantitative relationships between current modes, mean currents, winds, and intrusions?; (2) What is the residence time of water in the Main Basin recirculation?; (3) What is the relationship between the inflowing water in Possession Sound and the observed decrease in dissolved oxygen?

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